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U.S. ARMY TEST & EVALUATION COMMAND

TECHNICAL REPORT

DPG T68-106

# FIELD USE OF INTENSITY OF TURBULENCE, RICHARDSON'S NUMBER AND EDDY DIFFUSIVITY TO MAKE DIFFUSION CALCULATIONS

BY

ALBERT W. WALDRON, JR.

MARCH 1968

RDT & E PROJECT NO. IV025001A128
METEOROLOGICAL ASPECTS OF CB PROGRAM



DUGWAY PROVING GROUND
DUGWAY, UTAH

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# FIELD USE OF INTENSITY OF TURBULENCE, RICHARDSON'S NUMBER AND EDDY DIFFUSIVITY TO MAKE DIFFUSION CALCULATIONS

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ALBERT W. WALDRON, JR.

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RDT & E PROJECT NO. IV025001A128
Meteorological Aspects of CB Program

USATECOM PROJECT NO. 5-5-9955-01

U.S. ARMY TEST OPERATIONS DIRECTORATE
METEOROLOGICAL DIVISION
DUGWAY PROVING GROUND
DUGWAY, UTAH

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ABSTRACT

This report consists of five sections. Section I is an introduction to the report. Sections II through V treat related subjects. Section II demonstrates the accuracy to be expected from diffusion dosage calculations which make use of direct measurements of intensity of turbulence and wind speed. Section III uses a derived expression for the relationship of Richardson's number to intensity of turbulence and the resulting dosage calculations are discussed. Section IV tests the universality of the derived relationship of Richardson's number to intensity of turbulence. Section V relates the variance of vertical wind speeds at different sites and altitudes to Richardson's number. Section V further treats some of the problems involved in calculating and using eddy diffusivity to make dosage calculations, and also suggests a way of calculating eddy diffusivity at heights between the top of the surface boundary layer and the gradient wind level.

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FIELD USE OF INTENSITY OF TURBULENCE, RICHARDSON'S NUMBER AND EDDY DIFFUSIVITY TO MAKE DIFFUSION CALCULATIONS

## SECTION I. INTRODUCTION

### A. BACKGROUND

The U.S. Army has sponsored several instantaneous line source diffusion test series during the last fifteen years. For some of the earlier test series, only vertical wind and temperature profiles are available. For the more recent ones, turbulence intensity measurements have been made and are available. Sections II through V of this report deal with (1) the analysis of data collected from three of the U.S. Army test series and (2) results obtained from U.S. Air Force wind and temperature profiles collected at one of the army sites (Dallas TV tower). Wind and temperature profile data or bivane-measured values of intensity of turbulence ($i_Z$), can be used to make dosage calculations. It is also possible to estimate a value of intensity of turbulence, from the relationship of the vertical wind and temperature profiles to the intensity of turbulence. An outline of three methods for preparing dosage calculations based on the above considerations appears below. Applications of these methods to data constitute the body of Sections II through V of this technical report.

#### 1. Method 1

Method 1, section II, uses a directly measured intensity of turbulence to estimate the vertical standard deviation of the aerosol cloud particle distribution. This standard deviation is then substituted in an equation for dosage calculation which assumes a normal distribution of the aerosol cloud. Observed and calculated dosages are compared. This method demonstrates marked success for predicting dosages and for predicting the aerosol cloud touchdown distance.

#### 2. Method 2

Method 2, sections III and IV, involves estimating the vertical intensity of turbulence from Richardson's number. The estimated value of intensity of turbulence is then substituted in the same dosage equation used in section II. The relationship between Richardson's number and the intensity of turbulence is derived from the 1961 Dallas tower measurements of intensity of turbulence, wind speed and temperatures in the

9 meter to 91 meter, and 91 meter to 137 meter layers. Section III presents an independent data check of the adequacy of the relationship as a basis for preparing elevated line source dosage calculations for distances up to sixty miles. Section IV treats the 1953 city tests and consists of the analysis of ground dosages resulting from aerosol dissemination, from a moving automobile, in three different cities.

Surface roughness is greater in cities than it is for the rolling plains treated in sections II and III. Since the relationship between Richardson's number and intensity of turbulence is a function of roughness, the formula derived for less rough terrain would not be expected to apply over rougher surfaces (cities). This is treated in section IV. The relationship of Richardson's number and intensity of turbulence, found over Minneapolis, is independently checked over Winnipeg and further compared to a similar relationship obtained from the 1964-1966 Fort Wayne TV tower data where actual measurements of intensity of turbulence were available.

3. Method 3

Method 3, section V, uses the K or transfer theory approach, where K is the eddy diffusivity. The expression for the appropriate eddy diffusivity is derived from the equations of motion. This value of K is shown to be accurate for the preparation of vertical profile temperature forecasts. The adequacy of the same value of K for preparing aerosol dosage calculations is treated in section V.

## B. SUMMARY

Comparison of the three methods, indicates that (1) the use of bivane-measured intensity of turbulence to estimate aerosol cloud standard deviation produces the most useful estimates of surface dosages, (2) second best is the method of estimating the intensity of turbulence from Richardson's number and substitution in a diffusion equation which assumes the normal distribution of the aerosol cloud and (3) use of the eddy diffusivity method produces the least useful results.

## SECTION II. THE APPLICATION OF AN ELEVATED LINE SOURCE DIFFUSION FORMULA TO DOSAGE CALCULATIONS FOR DISTANCES UP TO 30 MILES FROM SOURCE *

### A. BACKGROUND

During the spring and summer of 1961, 34 elevated line source diffusion tests were conducted at night, at the Dallas tower test site, Cedar Hill, Tex., [1] where a 433 meter television tower was instrumented to measure temperature, wind direction and speed at several levels. Meteorology Research, Inc. installed bivanes, designed and manufactured by them, on the tower and was responsible for the reduction of data. Meteorology personnel from Dugway Proving Ground, Utah were responsible for the aerosol dissemination and sampling. The rotorod samplers used were developed by Metronics Associates, Inc., of Palo Alto, Calif.

These test results are used here to evaluate a current diffusion equation model and to define the turbulent layer in which such a model can be successfully used. The turbulent layer is defined in terms of Richardson's number and the vertical intensity of turbulence.

The Cedar Hill elevated line source tests represent the first diffusion experiment for intermediate ranges in which ground sampling, vertical tower sampling and bivane data were combined. The Porton Group [2] conducted elevated line source experiments in 1958 and 1959 using vertical gustiness meters and a vertical array of samplers on a balloon cable, but no associated ground sampling.

### B. EXPERIMENT DESCRIPTION

The sampling array used at the Dallas test site is shown in figure 1. Most of the tests were run using line E with a southerly wind flow. Line A was used for tests 9 and 10; line B for tests 11 and 34; line C for tests 35, 36, 37 and 38; and line D for tests 2 and 12. In every case, the elevated line source release was upwind from the television tower and perpendicular to the wind direction. The length of the dissemination line was about 22 miles for tests 1 through 12, and 25 miles for the remainder of the tests. The aerosol used was zinc cadmium sulfide,

*This section is a revised version of an article originally published in the Journal of Applied Meteorology, Vol. 2, No. 6, Dec. 1963.

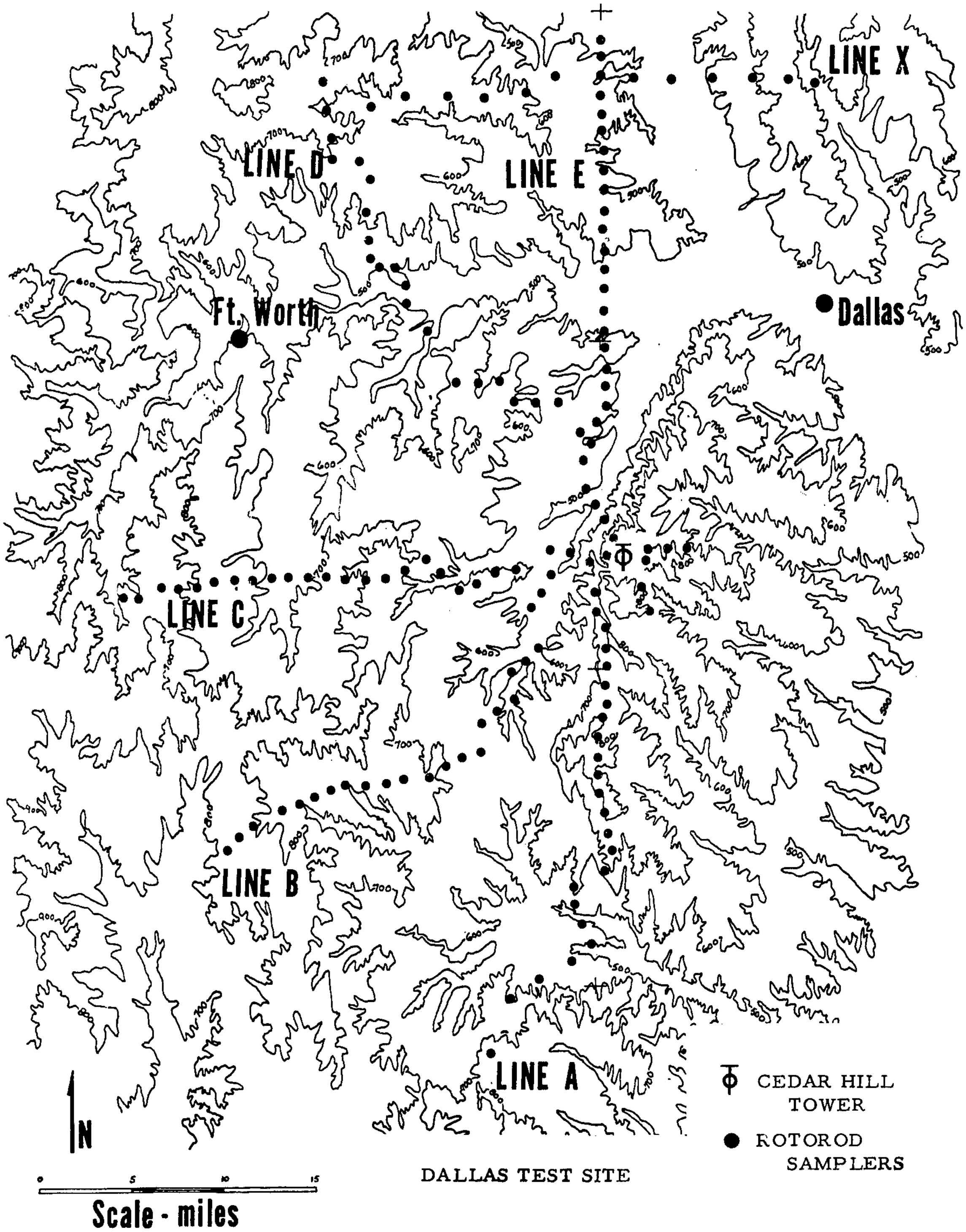


Figure 1 - Dallas Test Site

disseminated at effective rates of $3.816 \times 10^9$ and $3.339 \times 10^9$ particles/meter respectively, for the first and second series.

For tests 20 through 33, additional crossline sampling was used on line X, shown in figure 1. All particle sizes were less than 7.5 microns in diameter and all but three per cent were five microns, or less, in diamter. Bivanes were installed at 9.15, 45.7, 137.2, 228.7, and 320.1 meters on the tower. All tests were conducted at night during temperature inversion conditions. Observed dosages were compared to computed values based on the Calder [3] equation (1).

$$D(X,0,0) = (2/\pi)^{1/2} \frac{Q}{\sigma_z \bar{U}} \exp(-h^2/2\sigma_z^2) \tag{1}$$

where:

$D(X,0,0)$ = dosage in particle-minutes per liter measured at 1.5 meters

$Q$ = source strength in particles per centimeter

$\bar{U}$ = mean wind speed from surface to release height in cm. per min.

$h$ = release height in centimeters

$\sigma_z = 3\, i_{ze}^2\, x$ in centimeters

$x$ = downwind distance from source in centimeters

$i_{ze}$ = effective intensity of turbulence in radians

$h/i_{ze} = 2h_1/(i_{z_1} + i_{z_2}) + 2h_2/(i_{z_2} + i_{z_3}) + ----$ (An M.R.I. method, see reference [1])

$h_1$ = thickness of layer between bivane levels where $i_{z1}$ and $i_{z2}$ were measured.

$h_2$ = thickness of layer between the levels of $i_{z_2}$ and $i_{z_3}$

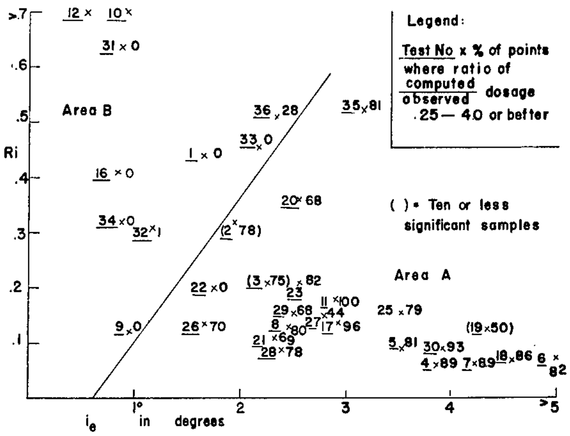


Figure 2 - Relationship to Richardson's number and intensity of turbulence of per cent of $\left(\frac{\text{computed dosage}}{\text{observed dosage}}\right)$ ratio of 0.25 to 4.0

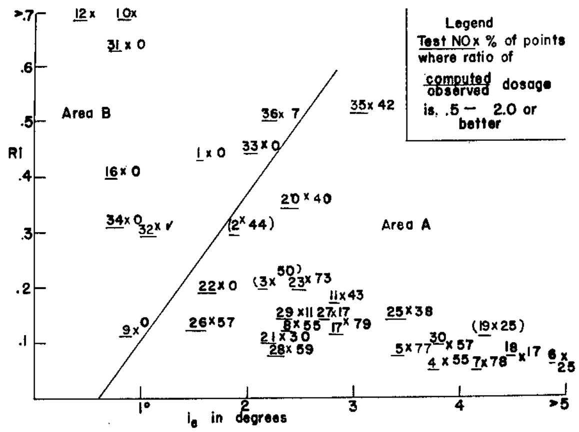


Figure 3 - Relationship to Richardson's number and intensity of turbulence of per cent of $\left(\frac{\text{computed dosage}}{\text{observed dosage}}\right)$ ratio of 0.50 to 2.0

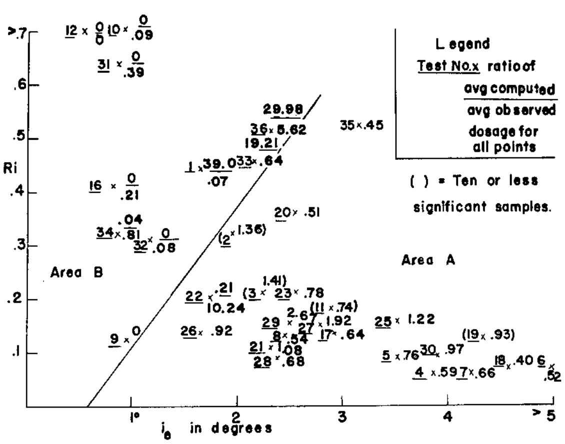


Figure 4 - Relationship to Richardson's number and intensity of turbulence of $\left(\frac{\text{average computed dosage}}{\text{average observed dosage}}\right)$ by test

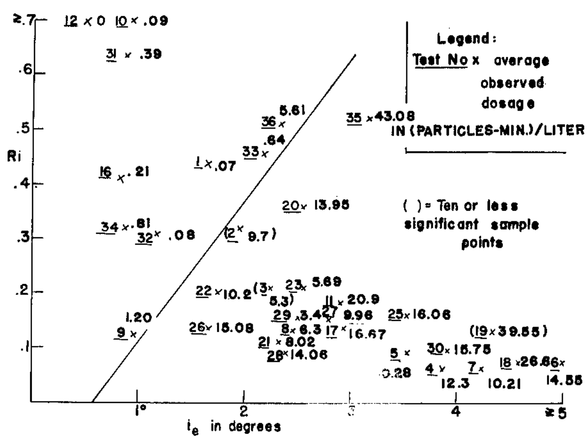


Figure 5 - Relationship to Richardson's number and intensity of turbulence of the average dosage for each test

$i_z$ = the vertical intensity of turbulence in radians as obtained from the standard deviation of the vertical wind direction fluctuations.

The relationship $\sigma_z = 3i_z^2 x$ was developed by Hay and Smith [2]. They show that the total turbulence spectrum should be used in computing the intensity of turbulence. Meteorology Research, Inc., showed that for nighttime tests at Cedar Hill, where the terrain was gently rolling grassland, most of the energy in the turbulence spectrum was contributed by waves having a time period of 6 min. or less [1]. Therefore, the basic sampling time used was 3 min. Since the variation of the intensity of turbulence, with time, was small, the value obtained by averaging for the first 10 min. of each test was considered sufficiently representative for computation purposes. A sigma meter, similar to the one used at Porton [4], was used to reduce all data, together with a high pass filter, with a 3 minute sampling time. Mean wind speeds during the Cedar Hill series of tests varied from 3.6 to 15.6 meters/second with the bulk of the winds greater than 6.7 m/sec. Hence, the time required for aerosol cloud passage at the last sampler, 30 mi. downwind, was usually 2 hrs. or less.

## C. COMPUTATIONS

Surface dosage calculations were made from 34 tests (Tables II through V). For 9 of the 36, the average ground dosage was negligible. For two others, tests 22 and 36, the calculations produced poor estimates of observed dosages. The average calculation for test 22 was .21 particle-minutes/liter compared to an observed average of 10.24. For test 34, the average calculation was 299.70 compared to an observed average dosage of 56.13 particles minutes per liter. Although calculated dosage estimates for tests 1 and 33 were also poor, the separation between areas "A" and "B" (Figure 2) is used to define cases where appreciable dosages can be expected at the ground.

In Figure 2, we see the frequency, for each test, of a "computed to observed dosage" ratio of 0.25 to 4.0. The test number is to the left of each point and the frequency of the given ratio is to the right. With the exception of test number 22, all test points in area "A" were correctly calculated within the given factor between 44 and 93 per cent of the time. The per cent of the ratios within the given ratio limits for all tests falling in area "A" (Figure 2) is 75.

In Figure 3, we see the frequencies, by test, of a "computed to observed dosage" ratio of 0.50 to 2.0. In area "A", there are 5 cases of 25 per cent or less, and 13 of 50 per cent or less, compared to one and three, respectively, in the previous figure. The average per cent within the desired limits for all points falling in area "A" (Figure 3) is 45 per cent.

Figure 4 shows the average ratio of "computed to observed dosage" for all points in each test. Note that for six tests falling in area "A", the average computed value is greater than the observed average. For the other 16, the observed figure is greater. In area "B", the computations are high, as expected for three tests, but essentially zero for the rest.

Figure 5 shows the average ground dosage for all tests. Note that only one test in area "B" received an appreciable average dosage. All of the 22 tests falling in area "A" received an average dosage of 3.53 particles minutes per liter or more.

D. ADEQUACY OF THE FORMULA FOR PREDICTING SURFACE DOSAGE MAGNITUDE

In the calculation of the effective intensity of turbulence, a simple method of correcting for the effect of the decrease of $i_z$ with height is used in equation (2).

$$h/i_{z_e} = 2h_1/(i_{z_1} + i_{z_2}) + 2h_2/(i_{z_2} + i_{z_3}) + \ldots \quad (2)$$

(See reference [1])

where: (Symbol definitions follow equation (1)).

This formula for the effective intensity of turbulence ($i_z$) weights the smaller values of $i_z$ more heavily. The calculations of the aerosol cloud standard deviation make use of the Hay and Smith short formula, equation (3).

$$\sigma_z = (2/3)\beta\, i_z^2 x \quad (3)$$

where: $\beta$ is the ratio of the Lagrangian and the Eulerian time scales and $i_z$ is in radians. Justification of the use of this short formula depends on the condition that $x/\beta$ is large compared with the calculated value of $\sigma_z$. If it is accepted that $\beta$ is a constant equal to 4.5 and that

$\sigma_Z$ is of the form given above, then the smallest ratio at Dallas for $(x/\beta)/_{\sigma Z}$ is 8.1. Hence, the Dallas data meets the Hay and Smith requirement that $x/\beta$ be much greater than $\sigma_Z$.

The decrease of turbulence with height at Dallas is associated with a markedly skewed observed vertical dosage distribution where the mode is at a higher elevation than the mean. Actually there is an average 1.6 ratio between the integrated dosages below the tower maximum dosage (or mode), and those above.

The relationship between calculated and observed dosages is perhaps best seen in Figure 6. Note that the observed and calculated dosages agree up to a distance of seven miles from source. Hence, for these distances, the formulas used seems adequate.

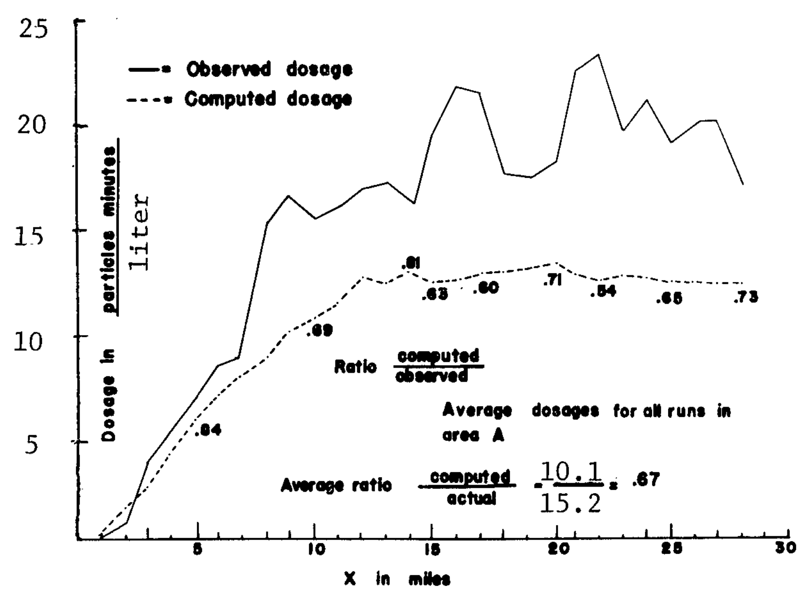


Figure 6. Average computed and observed dosages at various distances from source for all tests falling in area "A" in Figure 2

However, the overall tendency is for the computed dosages to be on the low side. The average ratio of "computed to observed dosages" for tests falling in area "A" (Figure 4) is .67. Figure 6 shows that the range of the average ratio of "computed to observed dosages" beyond eight miles, varies from a minimum of 0.5 to a maximum of 0.8, with the bulk of the ratios lying between 0.6 and 0.7. It is possible that the computations are on the low side because the decrease of $i_z$ with height has not been adequately corrected for here.

For ten of the Cedar Hill (Dallas Tower) tests falling in area "A", there is significant cross line sampling at distances of 28 to 30 miles from source (see example in Figure 7). The dosage values on such a line, resulting from an infinite line source, should all be equal. Actually, there were some edge effects here. Points obviously influenced by edge effects were eliminated, and the remainder of the points averaged out to a representative dosage figure. On this basis, comparison of "computed to observed dosages" were correct within a ratio of 0.5 to 2.0, eight out of ten times, compared to an average 4.5 out of 10 for all computations. Three of the computed values were high, four were low and three were in error by an amount less than 10 per cent of the observed value.

Tables I through V show the meteorological data, observed dosage data, and calculated dosage data for all of the Cedar Hill tests.

## E. ADEQUACY OF THE FORMULA FOR PREDICTING THE PRESENCE OF THE AEROSOL CLOUD AT THE GROUND

Perhaps the most useful forecast of aerosol surface dosages resulting from an elevated line source is the forecast of the presence, or absence, of the aerosol at the ground level. Such a forecast is less subject to errors than the dosage magnitude forecasts which are more clearly affected by the aerosol cloud skewness in the vertical. To avoid confusion with background counts, the presence of the aerosol is defined as a surface dosage of one or more particles minutes per liter. There are thirty-three Dallas tower tests for which the presence, or absence, of a significant dosage up to a distance of thirty miles is defined. For eleven of these tests, the FP cloud first reached the ground in four or fewer miles. In ten tests, the cloud reached the ground in thirteen or more miles. For the remaining twelve tests, the cloud reached the ground in the five through twelve mile interval. The skill score [5] for the Hay-Smith method in predicting the first touchdown distance class is .63 and the per cent of correct predictions is 76. Note in Table VI that no predicted touchdown distance is in error by more than one class. In Table VII, skill score for predicting yes or no for cloud touchdown in thirty miles is .65, and per cent correct is 89.

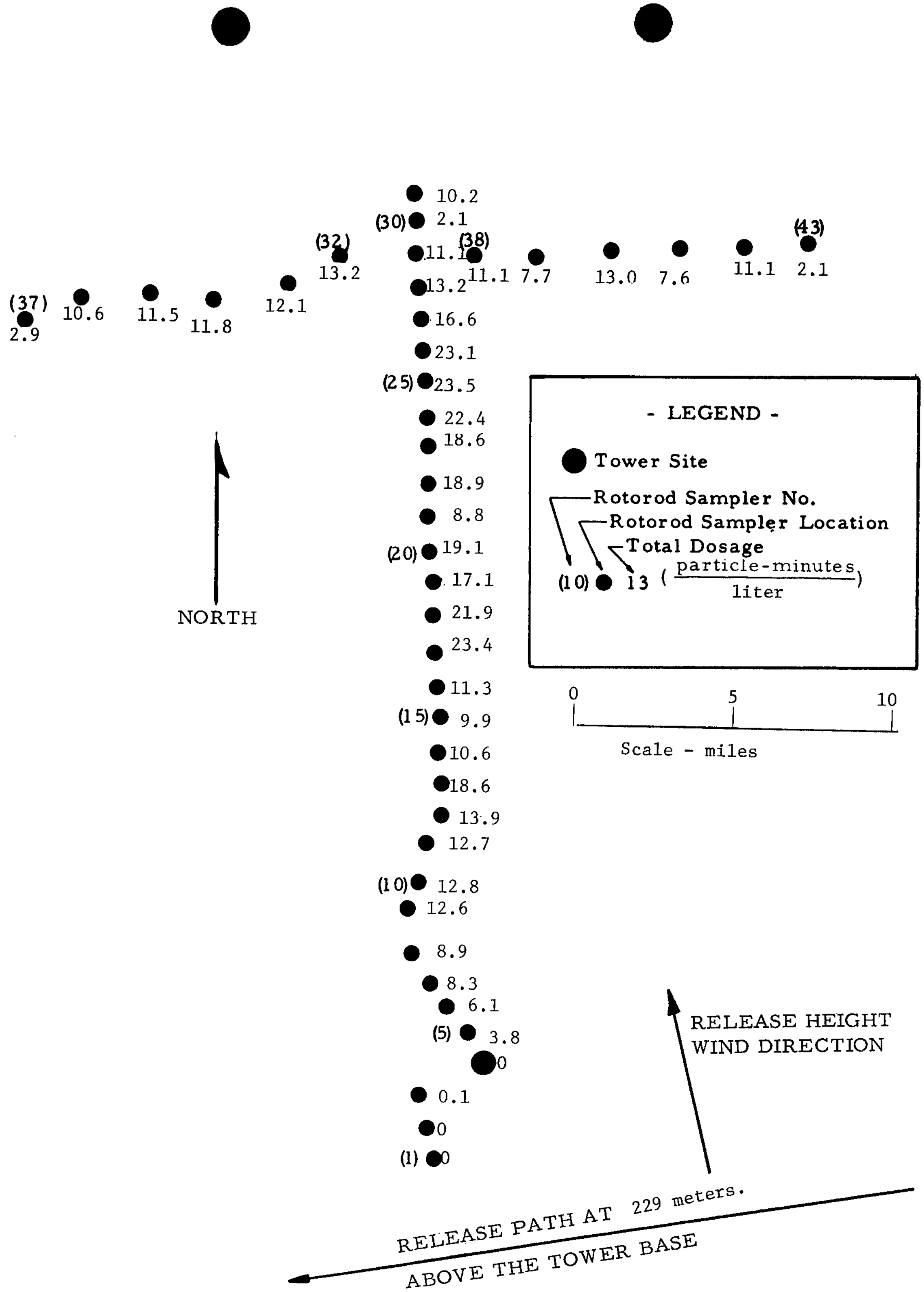


Figure 7 - Observed Surface Dosage Distribution For Test 28

TABLE I
METEOROLOGICAL DATA FOR ALL TESTS

| Test No. | Date | Time | Release height (meters) | $i_e$ (deg) | $\bar{U}$ (m/sec) | Richardson's number |
|---|---|---|---|---|---|---|
| 1 | 4/17/61 | 2019 | 116 | 1.65 | 4.0 | 0.44 |
| 2 | 4/18/61 | 0039 | 116 | 1.94 | 6.7 | 0.32 |
| 3 | 4/18/61 | 0459 | 116 | 2.24 | 7.1 | 0.21 |
| 4 | 4/19/61 | 2019 | 207 | 3.87 | 14.2 | 0.06 |
| 5 | 4/19/61 | 2319 | 207 | 3.51 | 13.9 | 0.09 |
| 6 | 4/22/61 | 2009 | 116 | 5.50 | 13.2 | 0.07 |
| 7 | 4/22/61 | 2309 | 207 | 4.22 | 13.9 | 0.06 |
| 8 | 4/23/61 | 0149 | 299 | 2.46 | 15.9 | 0.11 |
| 9 | 4/25/61 | 2019 | 207 | 0.96 | 8.7 | 0.12 |
| 10 | 4/26/61 | 0019 | 207 | 0.93 | 11.5 | 0.75 |
| 11 | 4/26/61 | 0359 | 116 | 2.90 | 10.5 | 0.18 |
| 12 | 4/28/61 | 1929 | 299 | 0.55 | 3.7 | 1.90 |
| 16 | 6/6/61 | 2019 | 229 | 0.84 | 7.4 | 0.41 |
| 17 | 6/6/61 | 2349 | 183 | 2.92 | 10.5 | 0.14 |
| 18 | 6/7/61 | 0319 | 137 | 4.57 | 9.3 | 0.07 |
| 19 | 6/8/61 | 1949 | 137 | 4.32 | 3.8 | 0.13 |
| 20 | 6/12/61 | 2029 | 229 | 2.55 | 10.3 | 0.36 |
| 21 | 6/12/61 | 2359 | 229 | 2.32 | 9.5 | 0.11 |
| 22 | 6/13/61 | 2009 | 320 | 1.74 | 12.2 | 0.20 |
| 23 | 6/13/61 | 2339 | 320 | 2.55 | 10.8 | 0.21 |
| 25 | 8/7/61 | 2104 | 137 | 3.51 | 6.5 | 0.16 |
| 26 | 8/8/61 | 0029 | 137 | 1.66 | 7.2 | 0.14 |
| 27 | 8/8/61 | 0459 | 137 | 2.80 | 7.6 | 0.14 |
| 28 | 8/9/61 | 2039 | 229 | 2.40 | 8.6 | 0.09 |
| 29 | 8/9/61 | 2359 | 229 | 2.50 | 9.3 | 0.15 |
| 30 | 8/10/61 | 0354 | 137 | 3.92 | 7.8 | 0.09 |
| 31 | 8/11/61 | 2024 | 320 | 0.88 | 8.6 | 0.64 |
| 32 | 8/11/61 | 2359 | 229 | 1.17 | 7.0 | 0.31 |
| 33 | 8/12/61 | 0329 | 137 | 2.18 | 7.7 | 0.46 |
| 34 | 8/14/61 | 2349 | 137 | 0.87 | 5.3 | 0.32 |
| 35 | 8/16/61 | 2054 | 137 | 3.19 | 6.7 | 0.52 |
| 36 | 8/17/61 | 0029 | 137 | 2.32 | 4.7 | 0.51 |
| 37 | 8/18/61 | 2019 | 137 | 2.00 | 7.2 | |
| 38 | 8/19/61 | 0005 | 137 | 2.00 | 4.5 | |

# TABLE II

## DOSAGE DATA FOR TESTS 1-10 IN PARTICLES MINUTES PER LITER

| Distance in Miles | Test 1 Obs | Test 1 Comp | Test 2 Obs | Test 2 Comp | Test 3 Obs | Test 3 Comp | Test 4 Obs | Test 4 Comp | Test 5 Obs | Test 5 Comp | Test 6 Obs | Test 6 Comp | Test 7 Obs | Test 7 Comp | Test 8 Obs | Test 8 Comp | Test 9 Obs | Test 9 Comp | Test 10 Obs | Test 10 Comp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .07 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2.90 | 0 | 0 | 0 | 0 | .11 | 0 | .07 | 0 |
| 2 | .04 | 0 | .11 | 0 | .07 | 0 | .39 | 0 | .46 | 0 | 3.67 | 18.53 | 1.98 | .04 | 0 | 0 | .07 | 0 | .07 | 0 |
| 3 | 0 | 0 | .14 | 0 | .32 | 0 | 3.49 | .39 | .35 | .04 | 9.64 | 19.80 | 11.26 | 1.41 | .04 | 0 | .07 | 0 | .11 | 0 |
| 4 | 0 | 0 | .18 | 0 | .28 | 0 | 6.14 | 2.54 | 3.81 | .85 | 14.08 | 17.51 | .56 | 4.91 | .04 | 0 | 0 | 0 | .11 | 0 |
| 5 | .04 | 0 | 2.05 | .04 | .39 | .04 | .78 | 5.51 | .04 | 2.96 | 7.66 | 15.14 | 5.15 | 7.98 | .07 | 0 | .07 | 0 | .04 | 0 |
| 6 | .04 | 0 | .78 | .53 | 1.98 | .49 | 3.35 | 7.94 | .42 | 5.51 | 13.91 | 13.13 | 8.12 | 9.78 | .14 | 0 | 0 | 0 | .14 | 0 |
| 7 | .07 | .07 | 15.46 | 2.19 | 3.71 | 2.08 | 6.53 | 9.43 | 1.24 | 7.62 | 9.92 | 11.19 | 4.34 | 10.55 | 0 | 0 | 0 | 0 | .04 | 0 |
| 8 | 0 | .56 | 10.31 | 5.54 | 9.21 | 5.19 | 16.77 | 10.20 | 2.33 | 9.07 | 25.45 | 10.27 | 11.61 | 10.73 | 1.41 | 0 | .07 | 0 | .07 | 0 |
| 9 | 0 | 1.98 | 11.12 | 10.13 | 10.34 | 9.57 | 16.73 | 10.48 | 13.84 | 10.03 | 33.37 | 9.21 | 18.99 | 10.55 | 4.27 | .04 | 0 | 0 | .07 | 0 |
| 10 | 0 | 4.84 | 6.92 | 15.32 | 16.20 | 14.44 | 18.60 | 10.48 | 17.40 | 10.48 | 20.83 | 8.37 | 18.07 | 6.32 | .14 | 0 | 0 | 0 | .18 | 0 |
| 11 | .04 | 9.07 | | | 5.54 | 19.24 | 15.78 | 10.27 | 10.97 | 10.73 | 22.95 | 7.66 | 14.40 | 9.81 | 4.45 | .32 | .07 | 0 | .11 | 0 |
| 12 | 0 | 14.47 | 10.13 | 25.03 | 4.87 | 23.61 | 13.63 | 9.95 | 14.58 | 10.70 | 25.56 | 7.06 | 11.26 | 9.39 | 3.18 | .60 | .14 | 0 | .04 | 0 |
| 13 | 0 | 20.51 | 12.21 | 28.95 | | | 15.14 | 9.67 | 14.76 | 10.55 | 21.67 | 6.53 | 13.13 | 8.97 | 3.92 | .99 | .35 | 0 | .07 | 0 |
| 14 | 0 | 26.79 | 18.89 | 32.16 | | | 16.27 | 9.32 | 13.83 | 10.31 | 15.25 | 6.07 | 11.90 | 8.54 | .42 | 1.45 | .71 | 0 | .21 | 0 |
| 15 | 0 | 32.86 | | | | | 17.69 | 8.90 | 12.11 | 10.06 | 8.83 | 5.68 | 5.68 | 12.99 | 7.10 | 1.94 | .49 | 0 | 0 | 0 |
| 16 | .21 | 38.61 | | | | | 16.06 | 8.61 | 14.26 | 9.78 | 8.30 | 5.33 | 9.53 | 7.73 | 5.47 | 2.47 | .56 | 0 | | |
| 17 | .07 | 43.81 | | | | | 20.30 | 8.26 | 10.13 | 9.50 | 13.03 | 5.01 | 10.91 | 7.38 | 7.10 | 3.00 | 3.39 | 0 | | |
| 18 | .21 | 48.30 | | | | | 20.40 | 7.91 | 13.49 | 9.18 | 9.39 | 4.77 | 11.37 | 7.06 | 2.12 | 3.49 | 3.53 | 0 | | |
| 19 | .04 | 52.28 | | | | | 20.26 | 7.59 | 13.73 | 8.86 | 13.87 | 4.48 | 9.64 | 6.78 | 7.84 | 3.99 | .18 | 0 | | |
| 20 | .64 | 55.63 | | | | | 18.78 | 7.31 | 13.20 | 8.61 | 15.64 | 4.27 | 10.87 | 6.50 | 8.58 | 4.41 | 5.86 | 0 | | |
| 21 | .07 | 58.39 | | | | | 20.37 | 7.02 | 13.20 | 8.30 | 16.17 | 4.09 | 9.64 | 6.21 | 8.75 | 4.77 | | | | |
| 22 | 0 | 60.61 | | | | | 18.07 | 6.78 | 11.90 | 8.01 | 13.87 | 3.92 | 9.85 | 5.97 | 8.01 | 5.12 | 5.68 | 0 | | |
| 23 | .07 | 62.38 | | | | | 14.44 | 6.53 | 12.96 | 7.77 | 14.93 | 3.74 | 11.54 | 5.75 | 9.85 | 5.40 | .78 | 0 | | |
| 24 | .07 | 63.79 | | | | | 9.85 | 6.32 | 11.15 | 7.48 | 14.26 | 3.57 | 11.61 | 5.54 | 7.38 | 5.65 | 1.45 | 0 | | |
| 25 | .07 | 64.81 | | | | | 6.57 | 6.07 | 11.54 | 7.27 | 15.53 | 3.42 | 9.32 | 5.33 | 7.80 | 5.86 | .07 | 0 | | |
| 26 | 0 | 65.55 | | | | | 6.39 | 5.86 | 11.08 | 7.06 | 14.54 | 3.32 | 10.48 | 5.15 | 7.48 | 6.04 | 0 | 0 | | |
| 27 | .07 | 66.04 | | | | | 4.27 | 5.68 | 10.63 | 6.85 | 11.61 | 3.18 | 9.35 | 4.98 | 8.75 | 6.18 | .07 | 0 | | |
| 28 | .07 | 66.26 | | | | | 4.24 | 5.51 | 7.45 | 6.64 | 13.52 | 3.11 | 7.87 | 4.80 | 7.70 | 6.28 | 0 | 0 | | |

# TABLE III

## DOSAGE DATA FOR TESTS 11-21 IN PARTICLES MINUTES PER LITER

| Distance in miles | Test 11 Obs | Test 11 Comp | Test 12 Obs | Test 12 Comp | Test 16 Obs | Test 16 Comp | Test 17 Obs | Test 17 Comp | Test 18 Obs | Test 18 Comp | Test 19 Obs | Test 19 Comp | Test 20 Obs | Test 20 Comp | Test 21 Obs | Test 21 Comp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | .04 | 0 | | | 0 | 0 | .11 | 0 | | | 0 | 0 | .07 | 0 |
| 2 | 1.66 | 0 | 0 | 0 | | | .04 | 0 | 2.37 | 6.53 | 68.41 | 9.53 | 0 | 0 | .18 | 0 |
| 3 | 2.51 | .99 | .04 | 0 | | | .04 | 0 | 27.18 | 17.33 | 1.55 | 36.08 | 0 | 0 | 0 | 0 |
| 4 | 12.11 | 6.32 | .04 | 0 | | | 1.16 | .11 | 25.38 | 21.07 | 64.25 | 49.67 | .04 | .49 | .07 | 0 |
| 5 | | | 0 | 0 | | | 1.69 | .95 | 33.01 | 21.11 | 23.97 | 52.63 | .14 | 2.22 | 1.69 | 0 |
| 6 | 16.87 | 19.34 | .04 | 0 | .04 | 0 | 10.48 | 2.89 | 34.63 | 19.87 | | | .49 | 4.69 | 4.73 | 0 |
| 7 | 68.45 | 22.91 | 0 | 0 | 0 | 0 | 21.18 | 5.47 | 26.37 | 18.32 | | | | | 1.27 | 0 |
| 8 | 49.98 | 24.71 | 0 | 0 | 0 | 0 | 32.55 | 8.01 | 34.24 | 16.80 | | | 7.70 | 8.90 | .53 | .11 |
| 9 | 12.74 | 25.38 | 0 | 0 | 0 | 0 | 35.37 | 10.10 | 37.67 | 15.43 | | | 3.95 | 10.17 | | |
| 10 | 10.27 | 25.31 | 0 | 0 | 0 | 0 | 32.97 | 11.68 | 32.26 | 14.23 | | | 2.61 | 10.94 | 3.78 | .92 |
| 11 | | | 0 | 0 | 0 | 0 | 21.82 | 12.78 | 35.62 | 13.17 | | | 1.24 | 11.37 | 9.14 | 1.73 |
| 12 | | | 0 | 0 | 0 | 0 | 19.74 | 13.48 | 31.28 | 12.21 | | | 1.41 | 11.51 | 15.53 | 2.75 |
| 13 | | | .07 | 0 | .04 | 0 | 22.95 | 13.91 | 23.58 | 11.40 | | | 4.02 | 11.51 | 15.39 | 3.88 |
| 14 | | | .04 | 0 | .18 | 0 | 18.53 | 14.08 | 25.06 | 10.66 | | | 11.44 | 11.37 | 14.51 | 5.08 |
| 15 | | | | | 0 | 0 | 18.03 | 14.12 | 27.50 | 10.03 | | | 13.59 | 11.15 | 14.26 | 6.25 |
| 16 | | | | | .04 | 0 | 16.91 | 14.01 | 24.96 | 9.46 | | | 15.71 | 10.91 | 15.74 | 7.31 |
| 17 | | | .04 | 0 | .04 | 0 | 20.12 | 13.84 | 26.58 | 8.93 | | | 17.47 | 10.63 | 12.88 | 8.30 |
| 18 | | | | | 0 | 0 | 18.18 | 13.59 | 28.31 | 8.47 | | | 21.67 | 10.31 | 11.08 | 9.14 |
| 19 | | | .04 | 0 | | | 18.14 | 13.31 | 24.46 | 8.05 | | | 32.62 | 10.03 | 10.48 | 9.88 |
| 20 | | | 0 | 0 | .24 | 0 | 16.94 | 13.03 | 28.20 | 7.66 | | | 35.51 | 9.71 | 8.08 | 10.52 |
| 21 | | | 0 | 0 | .95 | 0 | 17.19 | 12.71 | 24.78 | 7.31 | | | 48.96 | 9.43 | 6.60 | 11.01 |
| 22 | | | 0 | 0 | .21 | 0 | 17.12 | 12.39 | 25.03 | 6.99 | | | 48.86 | 9.11 | 5.47 | 11.44 |
| 23 | | | 0 | 0 | .04 | 0 | 13.31 | 12.07 | 24.50 | 6.71 | | | 20.58 | 8.86 | 6.35 | 11.79 |
| 24 | | | 0 | 0 | 0 | 0 | 11.40 | 11.79 | 25.63 | 6.42 | | | 9.64 | 8.58 | 5.93 | 12.04 |
| 25 | | | 0 | 0 | .04 | 0 | 10.13 | 11.47 | 26.33 | 6.18 | | | 17.23 | 8.33 | 6.35 | 12.50 |
| 26 | | | .04 | 0 | .46 | 0 | 12.71 | 11.15 | 26.02 | 5.97 | | | 11.72 | 8.08 | 5.61 | 12.36 |
| 27 | | | 0 | 0 | .42 | 0 | 13.10 | 10.87 | 25.52 | 5.75 | | | 8.68 | 7.84 | 4.84 | 12.46 |
| 28 | | | .04 | 0 | .28 | 0 | 12.92 | 10.59 | 24.36 | 5.54 | | | 7.17 | 7.62 | 4.34 | 12.50 |
| 29 | | | | | .04 | 0 | 12.67 | 10.34 | 19.42 | 5.37 | | | 6.71 | 7.41 | 2.40 | 12.53 |
| 30 | | | | | .21 | 0 | 11.86 | 10.06 | 18.81 | 5.19 | | | | | 2.58 | 12.50 |
| 31 | | | | | | | 12.74 | 9.81 | | | | | | | 2.33 | 12.46 |
| 32 | | | | | | | 11.37 | 9.57 | | | | | | | | |

## TABLE IV

### DOSAGE DATA FOR TESTS 22-30 IN PARTICLES MINUTES PER LITER

| Distance in | Test 22 | | Test 23 | | Test 25 | | Test 26 | | Test 27 | | Test 28 | | Test 29 | | Test 30 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| miles | Obs | Comp | Obs | Comp | Obs | Comp | Obs | Comp | Obs | Comp | Obs | Comp | Obs | Comp | Obs | Comp |
| 1 | | | .11 | 0 | | | | | | | | | | | 0 | 0 |
| 2 | .11 | 0 | 0 | 0 | | | | | | | | | | | .04 | 1.24 |
| 3 | .14 | 0 | .11 | 0 | .04 | 5.19 | 0 | 0 | 14.79 | .07 | 0 | 0 | 0 | 0 | 3.60 | 10.91 |
| 4 | .95 | 0 | .04 | 0 | .14 | 15.78 | 60.00 | 0 | 12.57 | 1.48 | 0 | 0 | 0 | 0 | 22.59 | 20.09 |
| 5 | .60 | 0 | 0 | 0 | 1.13 | 24.11 | 23.05 | 0 | 11.47 | 6.00 | .11 | 0 | 0 | 0 | 7.45 | 24.32 |
| 6 | .25 | 0 | .14 | 0 | 28.10 | 28.59 | .25 | 0 | 19.03 | 11.83 | 0 | 0 | 1.87 | 0 | 6.14 | 25.42 |
| 7 | .46 | 0 | .04 | 0 | 15.96 | 30.29 | .42 | 0 | 26.30 | 17.08 | 3.60 | .07 | .95 | .18 | 3.35 | 24.92 |
| 8 | 7.02 | 0 | .11 | 0 | 46.70 | 30.39 | 11.64 | .04 | 43.00 | 21.00 | 6.07 | .25 | 1.02 | .49 | 8.22 | 23.83 |
| 9 | 6.99 | 0 | 1.20 | .04 | 19.56 | 29.72 | 6.32 | .14 | 6.74 | 23.51 | 8.26 | .74 | .11 | 1.24 | 10.55 | 22.49 |
| 10 | 7.10 | 0 | 1.69 | .18 | 12.28 | 28.59 | 27.57 | .49 | .56 | 24.99 | 8.93 | 1.59 | .14 | 2.33 | 11.72 | 21.14 |
| 11 | 7.84 | 0 | 3.14 | .39 | 19.34 | 27.32 | 32.37 | 1.24 | .28 | 24.99 | 12.64 | 2.75 | .14 | 3.67 | 25.20 | 19.84 |
| 12 | 8.08 | 0 | 3.74 | .74 | 56.74 | 26.02 | 10.77 | 2.40 | 1.87 | 25.84 | 12.81 | 4.09 | .21 | 5.08 | 19.66 | 18.67 |
| 13 | 8.86 | 0 | 4.69 | 1.20 | 72.79 | 24.75 | 4.87 | 3.99 | 2.29 | 24.99 | 12.67 | 5.51 | 1.27 | 6.42 | 17.44 | 17.58 |
| 14 | 8.51 | 0 | 4.27 | 1.77 | 25.66 | 23.51 | 7.70 | 5.90 | 11.01 | 25.24 | 13.91 | 6.85 | 2.72 | 7.66 | 17.54 | 16.49 |
| 15 | 8.51 | 0 | 4.62 | 2.40 | 18.92 | 22.38 | 12.46 | 8.01 | 6.18 | 24.67 | 18.60 | 8.08 | 3.46 | 8.75 | 10.34 | 15.67 |
| 16 | 12.00 | 0 | 4.94 | 3.04 | 20.40 | 21.32 | 13.56 | 10.20 | 5.26 | 24.00 | 10.59 | 9.25 | 3.07 | 9.74 | 4.69 | 14.83 |
| 17 | 6.71 | 0 | 4.62 | 3.67 | 26.83 | 20.30 | 15.21 | 12.39 | 4.80 | 23.33 | 9.88 | 10.24 | 2.82 | 10.48 | 9.99 | 13.98 |
| 18 | 10.91 | 0 | 5.44 | 4.27 | 39.15 | 19.38 | 19.24 | 14.51 | 6.18 | 22.63 | 11.30 | 11.08 | 3.95 | 11.15 | 14.83 | 13.34 |
| 19 | 6.42 | .04 | 5.19 | 4.80 | 9.78 | 18.53 | 7.55 | 16.45 | 3.42 | 21.92 | 23.37 | 11.83 | 4.02 | 11.65 | 12.60 | 12.74 |
| 20 | 8.72 | .07 | 6.00 | 5.33 | 7.10 | 17.76 | 8.97 | 18.25 | 3.64 | 21.25 | 21.89 | 12.32 | 4.73 | 12.07 | 12.00 | 12.14 |
| 21 | 7.38 | .11 | 6.99 | 5.79 | 5.54 | 17.01 | 12.46 | 19.84 | | | 17.09 | 12.81 | 4.84 | 12.32 | 18.60 | 11.58 |
| 22 | 14.37 | .18 | 7.41 | 6.18 | 6.39 | 16.34 | 12.92 | 21.25 | | | 19.06 | 13.17 | 5.40 | 12.50 | 21.89 | 11.15 |
| 23 | 12.04 | .28 | 7.55 | 6.53 | 5.47 | 15.71 | 7.34 | 22.45 | | | 8.83 | 13.41 | 2.15 | 12.67 | 20.33 | 10.66 |
| 24 | 8.51 | .39 | 7.24 | 6.81 | 5.61 | 15.11 | 17.61 | 23.51 | | | 18.92 | 13.59 | 4.98 | 12.74 | 25.91 | 10.24 |
| 25 | 15.71 | .53 | 6.85 | 7.06 | 2.19 | 14.58 | 20.93 | 24.39 | | | 18.60 | 13.73 | 4.59 | 12.74 | 32.05 | 9.81 |
| 26 | 16.49 | .71 | 7.55 | 7.26 | 2.75 | 14.05 | 10.06 | 25.13 | | | 22.45 | 13.84 | 6.60 | 12.74 | 27.39 | 9.50 |
| 27 | 14.76 | .88 | 8.19 | 7.41 | 3.64 | 13.59 | 20.62 | 25.73 | | | 23.51 | 13.84 | 5.01 | 12.67 | 27.25 | 9.18 |
| 28 | 18.21 | 1.09 | 8.08 | 7.55 | 5.08 | 13.13 | 23.44 | 26.19 | | | 23.09 | 13.84 | 5.12 | 12.57 | 21.99 | 8.83 |
| 29 | | | 7.98 | 7.66 | 3.39 | 12.71 | 22.27 | 26.58 | | | 16.63 | 13.73 | 5.90 | 12.50 | 12.07 | 8.58 |
| 30 | | | 7.98 | 7.73 | 4.31 | 12.32 | 23.62 | 26.86 | | | 13.20 | 13.66 | 6.71 | 12.32 | 15.92 | 8.33 |
| 31 | | | | | .71 | 11.93 | 26.09 | 27.08 | | | 11.15 | 13.59 | 6.99 | 12.25 | | |
| 32 | | | | | | | 29.02 | 27.16 | | | 2.08 | 13.41 | 1.45 | 12.07 | | |
| 33 | | | | | | | 23.62 | 27.29 | | | 10.24 | 13.34 | 4.59 | 11.90 | | |

## F. CONCLUSION

In summary, use of the Hay-Smith short formula for $\sigma_Z$ results in calculated dosage values which are a reasonably good approximation of the observed surface dosage values for distances up to seven miles. Beyond that, the predicted dosages are on the low side. This is the result of the aerosol cloud skewness in the vertical and failure to fully correct for this in the calculation of $\sigma_Z$. However, even at distances of 28 to 30 miles from source, calculated dosages are within a factor of 0.5 to 2.0 of the representative observed dosages eight out of ten times, where representative dosage means an average of five to eight sampler results at the same distance from source.

## TABLE V

## DOSAGE DATA FOR TESTS 31-38 IN PARTICLES MINUTES PER LITER

| Dist. in miles | Test 31 Obs | Test 31 Comp | Test 32 Obs | Test 32 Comp | Test 33 Obs | Test 33 Comp | Test 34 Obs | Test 34 Comp | Test 35 Obs | Test 35 Comp | Test 36 Obs | Test 36 Comp | Test 37 Obs | Test 37 Comp | Test 38 Obs | Test 38 Comp |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | | .11 | 0 | 0 | 0 |
| 2 | | | | | | | | | 5.11 | 0 | | | .11 | 0 | .04 | 0 |
| 3 | | | 0 | 0 | | | .07 | 0 | 7.38 | 1.41 | .18 | 0 | .25 | 0 | .04 | 0 |
| 4 | 0 | 0 | 0 | 0 | | | 0 | 0 | 17.01 | 8.08 | .46 | 0 | .85 | 0 | 2.68 | 0 |
| 5 | 0 | 0 | 0 | 0 | | | 0 | 0 | 42.64 | 16.59 | .28 | .60 | 8.79 | 0 | 2.97 | 0 |
| 6 | 0 | 0 | 0 | 0 | 10.73 | .32 | .04 | 0 | 48.54 | 23.16 | .28 | 3.07 | .95 | .07 | .56 | .18 |
| 7 | 0 | 0 | 0 | 0 | .04 | 2.26 | .11 | 0 | 40.28 | 27.00 | .95 | 7.98 | 4.73 | .56 | .39 | .92 |
| 8 | .07 | 0 | .11 | 0 | .04 | 5.08 | .11 | 0 | 44.73 | 28.91 | .11 | 14.23 | 5.44 | 1.91 | 6.32 | 3.00 |
| 9 | 0 | 0 | .07 | 0 | 0 | 8.47 | .18 | 0 | 61.56 | 29.48 | 3.10 | 20.76 | 10.98 | 4.09 | 39.51 | 6.57 |
| 10 | .32 | 0 | .04 | 0 | .35 | 12.36 | .25 | 0 | 40.63 | 29.23 | | | 12.39 | 6.99 | 40.56 | 11.15 |
| 11 | .11 | 0 | .07 | 0 | .04 | 15.32 | .32 | 0 | 67.85 | 28.56 | .21 | 31.31 | 5.90 | 10.17 | 29.19 | 16.31 |
| 12 | .60 | 0 | 0 | 0 | 0 | 18.07 | .32 | 0 | 65.20 | 27.75 | .18 | 37.74 | 12.43 | 13.41 | 26.33 | 21.39 |
| 13 | .04 | 0 | .04 | 0 | .04 | 20.40 | .95 | 0 | 35.30 | 26.72 | .28 | 39.57 | 1.45 | 16.31 | 48.89 | 26.16 |
| 14 | 0 | 0 | .25 | 0 | 0 | 22.17 | .74 | 0 | 29.23 | 25.66 | .04 | 40.74 | 7.13 | 18.92 | 63.68 | 30.32 |
| 15 | 0 | 0 | 0 | 0 | .04 | 23.47 | .74 | 0 | 86.27 | 24.69 | .32 | 41.41 | 12.28 | 21.14 | 76.28 | 33.82 |
| 16 | 0 | 0 | .04 | 0 | .07 | 24.46 | 1.52 | 0 | 102.26 | 23.58 | .71 | 41.65 | 34.59 | 22.91 | 96.09 | 36.75 |
| 17 | 0 | 0 | 0 | 0 | .04 | 25.06 | 1.34 | 0 | 102.83 | 22.66 | | | 27.82 | 24.39 | 75.26 | 38.97 |
| 18 | .11 | 0 | .07 | 0 | 0 | 25.49 | 1.55 | 0 | 36.11 | 21.74 | | | 17.44 | 25.49 | 51.36 | 40.74 |
| 19 | .11 | 0 | .04 | 0 | .04 | 25.66 | 2.47 | 0 | 29.37 | 20.83 | | | 32.02 | 26.33 | 59.90 | 42.08 |
| 20 | .25 | 0 | 0 | 0 | .07 | 25.66 | | | 30.25 | 19.98 | 1.31 | 40.31 | 32.79 | 26.90 | 72.68 | 43.07 |
| 21 | .11 | 0 | 0 | 0 | .11 | 25.59 | .95 | 0 | 34.14 | 19.24 | 8.86 | 39.75 | 42.36 | 27.32 | 126.34 | 43.63 |
| 22 | .14 | 0 | 0 | 0 | .14 | 25.41 | .53 | 0 | 47.37 | 18.57 | 7.62 | 39.82 | 39.89 | 25.73 | 104.56 | 44.05 |
| 23 | .39 | 0 | 0 | 0 | .39 | 25.17 | 1.62 | 0 | 46.17 | 17.83 | 8.33 | 38.97 | 36.39 | 27.64 | 99.02 | 44.16 |
| 24 | .21 | 0 | .07 | 0 | .21 | 24.82 | 2.68 | 0 | 59.83 | 17.23 | 10.17 | 38.23 | 6.85 | 27.57 | 136.29 | 44.20 |
| 25 | .42 | 0 | .04 | 0 | .35 | 24.50 | 2.65 | 0 | 66.12 | 16.66 | 17.30 | 37.49 | 26.90 | 27.50 | 57.89 | 43.98 |
| 26 | .32 | 0 | 0 | 0 | .81 | 24.07 | 2.12 | 0 | 74.73 | 16.06 | 12.53 | 36.64 | 6.21 | 27.32 | 98.24 | 43.74 |
| 27 | .35 | 0 | .14 | 0 | | | | | 68.06 | 15.57 | 17.26 | 35.90 | 20.47 | 27.08 | 93.40 | 43.31 |
| 28 | 1.02 | 0 | .18 | 0 | | | .25 | 0 | 17.97 | 15.07 | 22.42 | 35.16 | 24.00 | 26.83 | 87.16 | 42.89 |
| 29 | .39 | 0 | .11 | .07 | | | .28 | 0 | 7.77 | 14.58 | 25.10 | 34.31 | 25.35 | 26.48 | 41.44 | 42.40 |
| 30 | .64 | 0 | 0 | .07 | | | 0 | .07 | 7.20 | 14.16 | 15.64 | 33.57 | | | | |
| 31 | .92 | 0 | .11 | .07 | | | .04 | .07 | 6.57 | 13.73 | | | | | | |
| 32 | .71 | 0 | .04 | .18 | | | .07 | .18 | 7.70 | 13.34 | | | | | | |
| 33 | .07 | 0 | | | | | .14 | .25 | | | | | | | | |
| 34 | .35 | 0 | | | | | .18 | .32 | | | | | | | | |

TABLE VI

CONTINGENCY TABLE FOR PREDICTED CLOUD TOUCHDOWN DISTANCE

Forecast of distance at which measured surface dosages were first equal to or greater than one particle minute per liter.

Distance in miles

| Observed touchdown distance, miles | | $\le 3$ | 4-12 | $\ge 13$ | Total |
|---|---|---|---|---|---|
| | $\le 3$ | 8 | 2 | 0 | 10 |
| | 4-12 | 1 | 9 | 3 | 13 |
| | $\ge 13$ | 0 | 3 | 7 | 10 |
| | Total | 9 | 14 | 10 | 33 |

Skill score = .63. Per cent correct = 76.

TABLE VII

CONTINGENCY TABLE FOR PREDICTING CLOUD PRESENCE AT THE GROUND IN THIRTY MILES

Forecast of presence of one particle minute per liter or more in thirty miles.

| | Yes | No | Total |
|---|---|---|---|
| Observed Yes | 21 | 1 | 22 |
| No | 2 | 4 | 6 |
| Total | 23 | 5 | 28 |

## SECTION III. AN INDEPENDENT DATA CHECK OF A RICHARDSON'S NUMBER FORMULA FOR INTENSITY OF TURBULENCE TO PREPARE DIFFUSION DOSAGE CALCULATIONS FOR DISTANCES UP TO 60 MILES FROM SOURCE

### A. BACKGROUND

The Windsoc I, 1959-60 temperature and wind profile data [6] plus aerosol sampling data is used here to make an independent data check of a Richardson's number formula for the vertical intensity of turbulence ($i_z$), which was developed from the more complete 1961 Dallas tower meteorological data [1]. (Refer to equation (4)). The upper air wind measurements used in the Windsoc I tests are pilot balloon soundings (pibal); the upper air temperatures are aircraft soundings. The Windsoc I wind, temperature, and aerosol dosage data used in this study have not been published.

### B. WINDSOC I EXPERIMENT

The Windsoc I elevated line source diffusion tests were conducted in Texas over a square, 125 miles to a side, with Fort Worth at the northern boundary and Fort Hood near the southern boundary. The variation in the ground elevation over the area is from a maximum of 476 meters to a minimum of 107 meters above sea level. The calculated roughness ($z_0$) for the grassy hilltop area in the vicinity of the Dallas TV tower, is 2 centimeters. However, in this independent data check, no use is made of the $z_0$ value.

For these tests, there were 84 surface samplers of the millipore filter sequential type which were placed 1.5 meters above the ground. There were also samplers on the Dallas TV tower and on a balloon cable located at Fort Hood (Figure 8).

For the first eight tests, the vertical temperature structure was determined by making measurements at 152 meter intervals every hour, using an L-20 aircraft.* These measurements were made at five different points over the grid. For tests 9 through 13, aircraft temperature soundings were made every hour over Fort Hood with measurements at 30.5 meter intervals from the surface to 1525 meters above the ground. Beginning with test 4, vertical temperatures were measured on the Fort Hood balloon cable at 30.5 meter intervals from

*Temperature-measuring equipment consisted of a thermistor located within a stagnation housing mounted in the airstream.

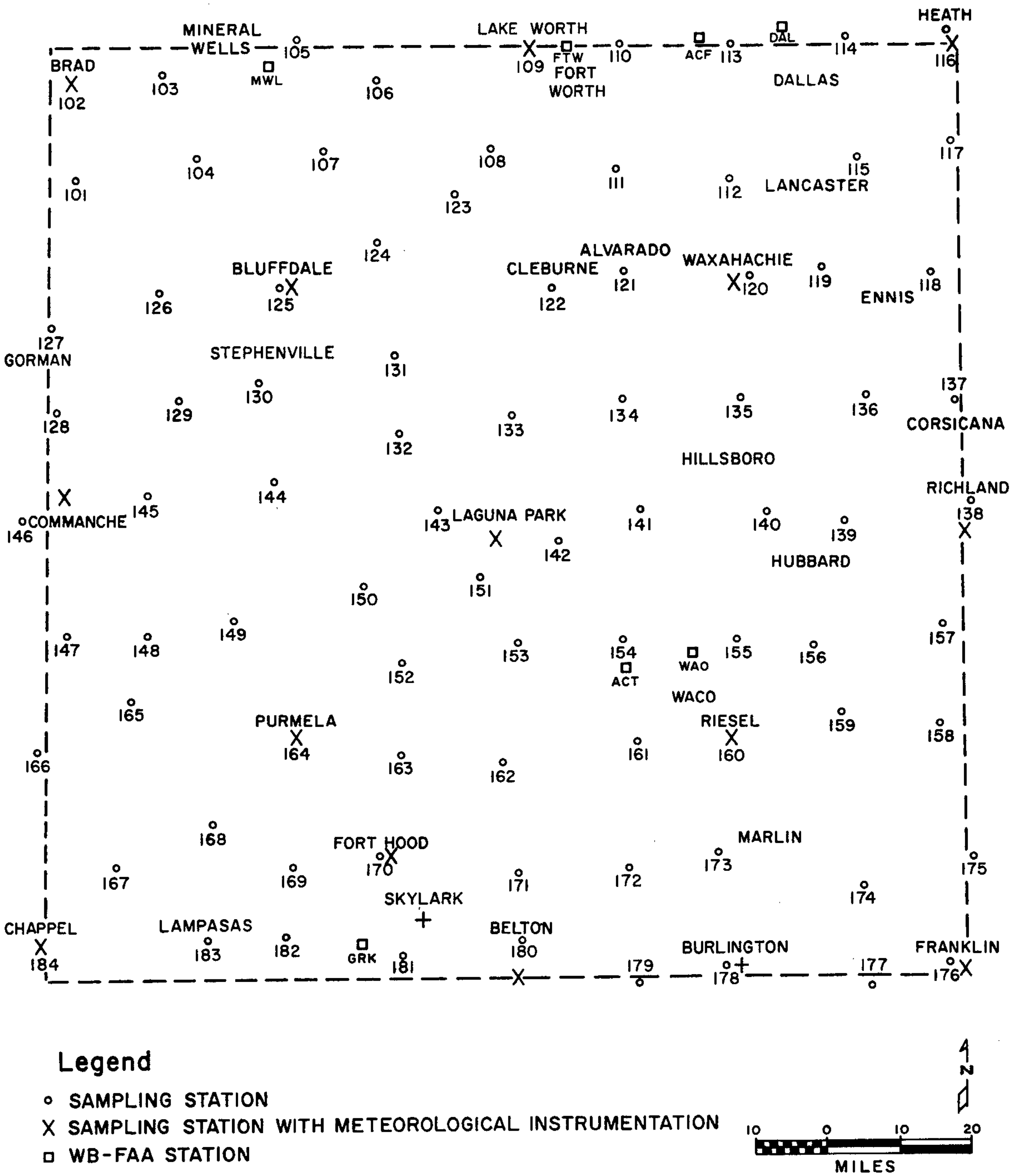


Figure 8 - Observational Network For Windsoc I

the surface to 152 meters. Pibal observations of the winds aloft were made every hour at fourteen locations over the area (Figure 8) at levels from surface to 1875 meters. In following the pibal, single theodolite readings were taken every thirty seconds, for a ten minute period, using thirty gram balloons. For the lowest 427 meters, the average balloon ascent rate was 210 meters per minute.

## C. EQUATIONS USED TO ESTIMATE THE VERTICAL INTENSITY OF TURBULENCE

The formula used to calculate the intensity of turbulence is derived from applying the least squares technique to the 45.7 meter and 137 meter $i_z$ data, plus associated Richardson's number of thirty-four 1961 Dallas tower tests. The equation (4) is:

$$i_z = 6.48\,(.657-Ri.)^* \tag{4}$$

where: the units of intensity of turbulence, $i_z$, are degrees and Richardson's number is determined from equation (5):

$$Ri = \frac{g(\partial T/\partial z + \Gamma)}{T(\partial U/\partial z)^2} \tag{5}$$

where: g = acceleration of gravity, T = absolute temperature
z = height above the surface, $\Gamma$ = dry adiabatic lapse rate
U = mean wind speed (averaged in time and space)

## D. DOSAGE CALCULATIONS USING TIME AND SPACE MEANS OF WINDSOC I DATA

Substitution of space and/or time meaned data for wind speed and temperature in equations (1) and (5) produces values for Richardson's number and intensity of tubulence ($i_z$). The release height wind speeds used represent the average result of fourteen pibal soundings which are averaged again for the cloud travel time. The temperature data for release height are, with three exceptions, averages for travel time at the location indicated. The surface temperatures are averages in time and space for the fourteen pibal station locations. The exceptions for release height temperatures are tests 7, 8 west and 8 east, where the 1800 CST Carter Field (Dallas) radiosonde is used.

*Sparseness of the data dictated a simple linear regression fit to the Dallas tower Richardson's number and $i_z$ data instead of the non-linear form to be found in references [9] and [12] .

To calculate dosage, the $i_z$ values obtained by using equations (4) and (5) (Table VIII) are used in the Calder diffusion model, equation (6).

$$D(X,0,0) = \frac{2Q \exp(-h^2/2\sigma_z^2)}{\sqrt{2\pi}\sigma_z \bar{U}} \quad (6)$$

where: $D(X,0,0)$ = surface dosage, $Q$ = effective source strength
$h$ = release height

$\sigma_z = 3i_z^2 x$,

$\bar{U}$ = the mean of the release height and two meter wind speeds which have already been meaned in space and time.

As a double check on the validity of the $\bar{U}$ value used in equation (6), the arrival time of the cloud maximum at the surface sampling stations is determined from the sequential sampling results. This time, averaged across the 60 mile sampler line, and the average release time (starting time plus ending time of release divided by two) are used to calculate the cloud center travel time and hence the travel speed (Table VIII). For eight of the eleven tests, the average cloud travel speed to the sixty mile line is 8.05 meters/second. The average wind speed used to make dosage calculations for the same tests is 7.69 meters/second.

TABLE VIII

WINDSOC I WIND SPEED, TEMPERATURE AND INTENSITY OF TURBULENCE DATA (14 PIBAL CASE)

| Test No. | Date | Release Time CST | Release Height Meters | 2 Meter Wind Speed M/Sec | Temperature Degrees C | Release Wind Speed M/Sec | Height Temperature Degrees C | Mean Wind Speed M/Sec | Cloud Travel Speed M/Sec | Richardson's No. | Turbulence intensity $i_z$ degrees |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8/13/59 | 1925-2037 | 198 | 2.48 | 26.28 | 10.24 | 25.53 | 6.36 | 5.99 | .134 | 3.39 |
| 2 | 8/15/59 | 2017-2123 | 183 | 3.13 | 25.56 | 11.62 | 26.89 | 7.38 | 8.76 | .260 | 2.57 |
| 3 | 8/18/59 | 1912-2015 | 198 | 2.68 | 30.67 | 11.62 | 29.56 | 7.15 | 7.96 | .0667 | 3.82 |
| 4 | 10/2/59 | 1813-1918 | 274 | 2.68 | 25.56 | 13.86 | 24.44 | 8.27 | 8.05 | .1155 | 3.50 |
| 6 | 10/7/59 | 1810-1921 | 198 | 1.79 | 20.78 | 12.07 | 25.56 | 6.93 | 10.24 | .4165 | 1.56 |
| 7 | 10/9/59 | 1900-2008 | 396 | .71 | 18.87 | 10.83 | 18.00 | 5.77 | MSG | .4000 | 1.66 |
| 8W | 10/12/59 | 1800-1906 | 305 | .63 | 23.20 | 10.80 | 23.50 | 5.56 | MSG | .3270 | 2.14 |
| 8E | 10/12/59 | 1800-1906 | 305 | 1.36 | 23.18 | 9.64 | 24.50 | 5.53 | MSG | .6430 | .091 |
| 10 | 2/12/60 | 1800-1921 | 198 | 2.24 | 1.11 | 9.61 | 1.44 | 5.92 | 5.77 | .2960 | 2.34 |
| 12 | 2/19/60 | 2055-2203 | 198 | 5.81 | 8.44 | 12.96 | 7.78 | 9.39 | 10.55 | .1735 | 3.13 |
| 13 | 2/22/60 | 1826-1953 | 290 | 4.69 | 10.33 | 15.87 | 10.78 | 10.28 | 7.15 | .2638 | 2.55 |

# TABLE IX

## WINDSOC I DOSAGE CALCULATIONS (PARTICLES MINUTES PER LITER)

| Test No. | Distance miles | 15 | 30 | 45 | 60 | Avg | Calc./Obs. | Touch-down Dist. miles | Location of Temperature sounding |
|---|---|---|---|---|---|---|---|---|---|
| 1 | a. calculated | 57.26 | 36.04 | 25.06 | 19.10 | 34.36 | 1.40 | 4 | Chilton Aircraft |
| | b. calculated | 0 | 0 | 0 | 0 | 0 | 0 | 90 | sounding |
| | c. observed | 10.98 | 35.94 | 31.10 | 20.40 | 24.60 | | 0 | |
| 2 | a. calculated | 52.95 | 47.83 | 36.72 | 27.82 | 41.09 | 1.06 | 6 | Burlington Aircraft |
| | b. calculated | 20.65 | 124.71 | 131.95 | 116.35 | 98.42 | 2.53 | 12 | sounding |
| | c. observed | 39.85 | 52.63 | 28.38 | 34.49 | 38.83 | | 3 | |
| 3 | a. calculated | 45.04 | 25.95 | 17.79 | 13.48 | 25.56 | .88 | 3 | Burlington Aircraft |
| | b. calculated | 51.75 | 35.94 | 25.42 | 19.45 | 33.15 | 1.14 | 5 | sounding |
| | c. observed | 38.65 | 33.22 | 21.43 | 22.56 | 28.95 | | 2 | |
| 4 | a. calculated | 33.46 | 24.57 | 17.61 | 13.59 | 22.31 | 1.23 | 5 | Skylark Aircraft |
| | b. calculated | 41.12 | 30.25 | 21.64 | 16.66 | 27.43 | 1.51 | 7 | sounding |
| | c. observed | 8.44 | 21.89 | 25.35 | 18.11 | 18.45 | | 8 | |
| 6 | a. calculated | .35 | 30.64 | 52.60 | 55.07 | 34.66 | 2.99 | 17 | Lampasas Aircraft |
| | b. calculated | 0 | .46 | 13.59 | 101.59 | 28.91 | 2.50 | 33 | sounding |
| | c. observed | 5.22 | 5.79 | 11.23 | 24.15 | 11.58 | | 10 | |
| 7 | a. calculated | 0 | .88 | 11.23 | 23.62 | 8.93 | | 31 | Amon Carter Field |
| | b. calculated | 0 | 0 | 0 | 0 | 0 | | >100 | (ACF) radiosonde |
| | c. observed | .11 | .04 | .04 | .04 | .05 | | 130 | |
| 8 | a. calculated | 2.26 | 35.58 | 44.73 | 42.04 | 31.13 | 8.32 | 14 | Amon Carter Field |
| West | b. calculated | 0 | 0 | 0 | 0 | 0 | | >100 | (ACF) radiosonde |
| | c. observed | 1.09 | 2.51 | 1.31 | 10.02 | 3.74 | | 10 | |
| 8 | a. calculated | 0 | .11 | 5.90 | 20.47 | 6.64 | | 37 | Amon Carter Field |
| East | b. calculated | 0 | 0 | 0 | 0 | 0 | | >100 | (ACF) radiosonde |
| | c. observed | .04 | .04 | .11 | .28 | .11 | | 90 | |
| 10 | a. calculated | 45.43 | 62.62 | 50.37 | 40.21 | 49.67 | 1.06 | 8 | Ft. Hood Aircraft |
| | b. calculated | 50.94 | 31.73 | 22.03 | 16.73 | 30.37 | .65 | 4 | sounding |
| | c. observed | 58.74 | 47.16 | 46.53 | 33.36 | 46.45 | | 6 | |
| 12 | a. calculated | 40.67 | 27.85 | 19.63 | 15.00 | 25.77 | 2.12 | 5 | Ft. Hood Aircraft |
| | b. calculated | 34.52 | 46.31 | 37.10 | 29.65 | 36.89 | 3.05 | 8 | sounding |
| | c. observed | 18.04 | 11.23 | 10.34 | 8.83 | 12.11 | | 4 | |
| 13 | a. calculated | 11.01 | 25.49 | 22.52 | 18.71 | 19.42 | .40 | 10 | Ft. Hood Aircraft |
| | b. calculated | 13.70 | 32.51 | 28.91 | 24.00 | 24.78 | .51 | 10 | sounding |
| | c. observed | 98.45 | 48.71 | 22.38 | 26.16 | 48.93 | | 7 | |
| Avg | a. calculated | 26.23 | 28.88 | 27.57 | 26.26 | 27.22 | | 8* | |
| | b. calculated | 19.34 | 27.46 | 25.52 | 29.48 | 25.42 | | | |
| | c. observed | 25.42 | 23.55 | 18.00 | 17.93 | 21.22 | | 5* | |
| | a/c | 1.03 | 1.23 | 1.53 | 1.46 | 1.31 | | 1.6 | |
| | b/c | .76 | 1.16 | 1.42 | 1.64 | 1.19 | | | |

Calculation a. was made using a value of Richardson's number prepared from the space average of fourteen pilot balloon soundings taken hourly which in turn were averaged for the time period between release time and the arrival time at the sixty mile surface samplers. The temperatures used were taken at one point but were averaged for the same time period.

Calculation b. was prepared using the average of three release-time pibals taken along the release line. The temperature sounding used was also for release time. The normalized source strength used above was $9.41 \times 10^9$ particles/meter. The disseminator efficiency was .50, so that effective normalized source strength is $4.75 \times 10^9$ particles per meter. Observed dosage values represent an average of from one to nine samplers (see table 9. for detail).

* Omitted trials 7 and 8 East in average.

Comparison of the calculated dosage to the observed dosage values shows a standard error of 27.94 particles minutes per liter. The average absolute error is 18.33. The average ratio of calculated dosage to the observed is 1.31. The indicated skill score of this system in predicting that the surface dosage will be 1 particle minute per liter or more in 30 miles is 1.0. Per cent correct is 100. From Table XI it can be seen that the ratio of calculated dosage to observed average dosage is .67 to 1.5, fifty per cent of the time. Twenty-five per cent of the time this ratio is less than 0.2 or more than 5.

## E. DOSAGE CALCULATIONS USING INSTANTANEOUS AEROSOL RELEASE TIME DATA

In the following treatment, the same method outlined above is applied to release time data (Table X). Three pilot balloon soundings (taken at Chappel, Belton and Franklin) are used together with a single aircraft temperature sounding taken along the release line during dissemination. The surface temperatures and wind speeds are the averages for release time of the three pibal station measurements. For tests 8 west and 8 east, the release line data is broken into two halves, the western and the eastern, in order to make calculations.

For these dosage calculations, comparison to the observed dosages produces a standard error of 31.8 particles minutes per liter. The average absolute error is 18.6 particles minutes/liter. The

TABLE X

WINDSOC I WIND SPEED, TEMPERATURE AND INTENSITY OF TURBULENCE DATA (3 PIBAL CASE)

| Test No. | Date | Release Time CST | Release Height Meters | 2 Meter Wind Speed M/Sec | 2 Meter Temperature degrees C | Release Height Wind speed M/Sec | Release Height Temperature degrees C | Mean Wind speed M/Sec | Cloud Travel speed M/Sec | Richardson's No. | Turbulence intensity $i_z$ degrees |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 8/13/59 | 1925-2307 | 198 | 3.58 | 26.98 | 10.27 | 28.80 | 6.92 | 5.99 | .5470 | .713 |
| 2 | 8/15/59 | 2017-2123 | 183 | 1.34 | 24.89 | 4.83 | 26.89 | 3.08 | 8.76 | .3800 | 1.80 |
| 3 | 8/18/59 | 1912-2015 | 198 | 4.16 | 30.33 | 10.59 | 29.44 | 7.38 | 7.96 | .1780 | 3.10 |
| 4 | 10/2/59 | 1813-1918 | 274 | 1.37 | 26.83 | 12.10 | 26.69 | 6.74 | 8.05 | .2030 | 2.94 |
| 6 | 10/7/59 | 1810-1921 | 198 | 1.73 | 24.22 | 9.01 | 26.22 | 5.37 | 10.24 | .488 | 1.10 |
| 7 | 10/9/59 | 1900-2008 | 396 | .04 | 21.74 | 6.75 | 21.93 | 3.40 | | 1.505 | |
| 8W | 10/12/59 | 1800-1906 | 305 | .22 | 25.78 | 6.46 | 26.10 | 3.34 | | .87 | |
| 8E | 10/12/59 | 1800-1906 | 305 | .22 | 24.44 | 4.55 | 26.00 | 2.39 | | 2.26 | |
| 10 | 2/12/60 | 1800-1921 | 198 | 2.37 | 1.89 | 11.80 | 1.69 | 7.08 | 5.77 | .128 | 3.43 |
| 12 | 2/19/60 | 2055-2203 | 198 | 5.05 | 8.96 | 10.88 | 8.42 | 7.97 | 10.55 | .294 | 2.35 |
| 13 | 2/22/60 | 1826-1953 | 290 | 2.82 | 12.33 | 13.34 | 12.39 | 8.08 | 7.15 | .265 | 2.54 |

average ratio of the calculated dosage to the observed dosage is 1.18. The skill score obtained in predicting that the surface dosage will be 1 particle minute per liter or more, in 30 miles, is 0.42. The per cent correct is 73. Table XI shows that nine per cent fewer of the instantaneous data cases are within a factor or divisor of three of the observed value, as compared to the calculations prepared from data averaged in time and space.

Rank method [5] comparison of the calculation error using this method to the calculation error made using averaged data indicate the the methods are not significantly different at the five per cent level. Correct prediction of when the aerosol cloud will reach the ground is important however, and it should be noted that the method using data from a completely instrumented tower produces a skill score of 0.65. (Refer to Section II, paragraph E.) Averaged data for Windsoc I produces a skill score of 1.0 and release time data produces a score of 0.42.

TABLE XI

FREQUENCY OF A GIVEN RANGE OF (CALCULATED/OBSERVED) DOSAGE

Frequency of given ratios of calculated to observed dosage in per cent.

| Ratios | +.67-1.5 | .50-2.0 | .33-3.0 | .25-4.0 | .20-5.0 |
|---|---|---|---|---|---|
| Fourteen pibal case | 50 | 59 | 68 | 70 | 75 |
| Three pibal case | 48 | 54 | 59 | 66 | 75 |

## F. ESTIMATE OF WINDSOC I OBSERVED DOSAGE RELIABILITY

Table XII shows the coefficient of variability of surface dosages as determined from the ratio of the standard deviation of dosages at any given distance from source, to the mean dosage at the same distance.

TABLE XII

COEFFICIENT OF VARIABILITY (STANDARD DEVIATION OF THE OBSERVED DOSAGES DIVIDED BY THE MEAN DOSAGE AT A GIVEN DISTANCE FROM SOURCE)

| Test No. | 15 mi. | No. of Samplers | 30 mi. | No. of Samplers | 45 mi. | No. of Samplers | 60 mi. | No. of Samplers |
|---|---|---|---|---|---|---|---|---|
| 1 | .79 | 5 | 1.03 | 4 | .31 | 5 | .22 | 6 |
| 2 | .90 | 5 | 1.30 | 5 | .54 | 8 | .69 | 7 |
| 3 | .47 | 6 | .35 | 7 | .42 | 9 | .58 | 5 |
| 4 | .55 | 4 | .87 | 7 | .52 | 7 | .58 | 5 |
| 6 | .96 | 8 | .47 | 7 | .92 | 7 | .74 | 6 |
| 10 | | 2 | .46 | 4 | .83 | 3 | .43 | 7 |
| 12 | .35 | 4 | .37 | 6 | .51 | 7 | .71 | 6 |
| 13 | | 1 | .46 | 4 | .88 | 3 | .60 | 5 |
| Mean | .67 | | .66 | | .62 | | .57 | |

In order to make some estimate of the reliability of the Windsoc I sampling data, it appears worth while to compare the measured dosage variability to results obtained from other tests at different times, or even other sites. The Dallas tower 1961 tests [1] were conducted over the same site used for Windsoc I. On ten of the Dallas tests, there was a sampler line perpendicular to the wind direction, approximately twenty-nine miles from source. (Figure 7.) The average release height for the 1961 Dallas tests was 210 meters above the tower base compared to an average release height of 220 meters above the terrain for Windsoc I. The average number of samplers on the Dallas tower crosswind line was nine. The average ratio on this line of the dosage standard deviation to the mean dosage is 0.44 with a minimum ratio of 0.16 and a maximum of 0.76. For the Dallas tests, the average per cent of observed dosages within one standard deviation of the corresponding thirty-mile mean is 67%. For the Windsoc I tests, thirty miles from source, the average per cent of observed dosages within one standard deviation of the corresponding mean is 57%.

For the 1953 city tests, conducted by the Ralph M. Parsons Co. [7], at Minneapolis, St. Louis, and Winnipeg, one might expect the relative dosage variability to be large due to the varying building heights and the alternate street-building-street pattern. The source was a surface instantaneous line source. Actually, for 1.5 meter sampling at a distance from source up to five miles, the average ratio of dosage standard deviation to the mean dosage at the same distance for the stable case, nighttime tests is 0.35 with a maximum value of 0.514 over the Minneapolis industrial area. Otherwise, the range is from 0.241 over the St. Louis suburbs to 0.407 for Minneapolis citywide. These figures are calculated from an average of five millipore filter samplers placed along a street at a constant downwind distances from source. (Refer to Tables XV and XVIII.)

It is also possible to compare the dosage variability above to that obtained from tests of smaller scale. Such tests have been conducted at Dugway where an estimated value of roughness $z_0$ is one centimeter. For a series of thirteen surface line source, nighttime tests conducted at Dugway during the years 1964 and 1965 [8], the ratio of dosage standard deviation to the mean dosage is calculated for a line of twenty-seven samplers, 366 meters from source. The average ratio of dosage standard deviation to the mean is 0.329 with a minimum value of 0.21 and a maximum of 0.46. The aerosol used in this case was B.G. (Bacillus globigii). The samplers were bubblers (A.G.I. 615 impinger coupled with a preimpinger) placed five feet above the ground. At Dugway, one to five micron fluorescent particle clouds have been found to be an adequate tracer for B.G. Hence, sampling results from different aerosols should be comparable.

In summary, the Windsoc I coefficient of variability of 0.66 at a distance 30 miles from source compares to the Dallas tower 1961 test series value of 0.44 at a similar distance. For other smaller scale nighttime line source tests, the coefficient of variability ranges from 0.21 to 0.51 and averages 0.34, also considerably less than the Windsoc I figure. On the Windsoc I tests, some of the samplers were turned on after the aerosol cloud arrived. Hence, there is some reason to believe that the calculation of Windsoc I dosages would verify better with a more adequate sampling technique.

## G. CONCLUSION

In conclusion, the satisfactory verification of the Richardson's number formula for $i_z$ on the Windsoc I data does not prove the universality of that relationship. Variations of terrain roughness from site to site must be considered, as well as the depth of the atmospheric layer involved. Also, a different formula might have to be developed for negative values of Richardson's number which occur during unstable conditions. It can be concluded, however, that over similar terrain and with slightly stable temperature stratification, that the use of the method outlined in paragraph E will produce positive skill in predicting whether the surface dosages will or will not equal or exceed 1 particle minute per liter for distances up to and including thirty miles.

## SECTION IV. AN ANALYSIS OF THE 1953 CITY DIFFUSION TESTS*

### A. BACKGROUND

During the year 1953, city diffusion tests for the Army were conducted by the Ralph M. Parsons Co. in Minneapolis, St. Louis, and Winnipeg [7]. The aerosol used was a one to five micron fluorescent particulate, zinc cadmium sulphide. The disseminator was a truck-born blower. Source types used were five-minute continuous point sources, and truck-born cross-wind line sources disseminated at the two meter level. The disseminating truck speed varied from an average figure of three miles per hour, for industrial area tests, to fifteen miles per hour, for citywide tests. For all line source calculations, it is assumed that the source type is instantaneous line. Meteorological instrumentation included wind-measuring equipment at the two meter level, various roof levels, and at the airports. Wiresondes were used to obtain the vertical temperature distribution in downtown sections, suburbs, and undeveloped areas. Aerosol sampling was by millipore filter samplers, in a 10 filter sequence. There were approximately 80 samplers per test at the two meter level, in addition to sampling at elevation, inside and outside the buildings.

### B. ANALYSIS METHOD

The 1953 city data is used to estimate the dosage variability within a city for instantaneous line sources, to estimate the vertical intensity of turbulence from dosage and wind speed data to test the applicability of Richardson's number as a means of estimating the vertical intensity of turbulence, to determine the change rate of the aerosol cloud vertical standard deviation ($\sigma_z$) with distance and to determine the sampled aerosol dosage distribution with height. Conditions are also compared for different cities and for the adjacent countryside.

Most of the 1953 tests were conducted at night. The average values of $i_z$ are estimated from the average cross-wind dosages at constant distance from source, where the source is instantaneous line type. The dosage formula used for the estimate is:

*This section is a revised version of a talk presented at the 1964 Salt Lake City AMS Meeting.

$$\text{Dosage} = D(X,0,0) = (2/\pi)^{\frac{1}{2}} Q/(\sigma_z \bar{U}) \quad (7)$$

where: Q is the source strength in particles per centimeter, (8) $\sigma_z = 3i_z^2x$ in centimeters; $i_z$ is the vertical intensity of turbulence in radians; x is the distance from source in centimeters; $\bar{U}$ is the average 2-48.8 meter wind speed in cm/minute; and D is the dosage in particles minutes per liter.

## C. TYPE OF METEOROLOGICAL DATA COLLECTED

No turbulence measurements were taken during the 1953 city tests. Winds permitting wiresonde temperature measurements were taken at various in-city locations. Upper winds were measured on the tops of buildings of various heights. In cases where in-city upper wind or vertical temperature profiles were not measured, airport radiosonde and wind-aloft data was used. Two meter winds were measured on the tops of cars parked about 46 meters upwind of the dissemination line and at the downwind edge of the sampling grid. The cars were parked before release time on the downwind side of a street, not in the lee of a building and preferably on the downwind side of an intersection, or facing an open area. Car-top wind measurements were made with a sensitive microtorque wind vane and an Alnor Velometer.

## D. LINE SOURCE RESULTS FOR MINN., ST. LOUIS AND WINNIPEG

### 1. Minneapolis

There were sixteen successful two meter line source tests in Minneapolis. The type of meteorological data used can be seen in Table XIII and the results of the Richardson's number, $i_z$ and dosage variability calculations in Tables XIV and XV. The smallest estimated value of $i_z$ is 5.7 degrees; the largest is 18.5 degrees.

At approximately one mile from source, the normalized dosage, $D\bar{U}x/Q$, varies from a minimum value of 3.77 to a maximum of 21.97. Hence the ratio of the maximum to the minimum value is 5.8. If it is assumed that dosage varies with $x^{-b}$, the maximum value obtained for "b" is 1.37 in a Minneapolis industrial area test. The minimum value is 0.75 for a suburban test. Dosage figures used to calculate "b" are shown in Table XV. It is possible that the contamination level has significantly influenced dosage values of less than eight particles minutes per liter so that values of "b" obtained from such small dosages are less reliable. Note, however, that both the maximum and minimum

TABLE XIII. LOCATION OF MINNEAPOLIS MEASURED WINDS AND TEMPERATURES

(Wirth Park is 4300 meters west of the downtown area; St. Cloud is 60 miles northwest of Minneapolis; and Clinton school is 2600 meters south of the downtown area. The business area wiresonde was taken near 918 3rd Ave. South, which is just outside the area of tall buildings and 805 meters south of the central business district.)

| Test No. | Temperature measurement 2 meter and 48.8 meter | Wind measurement 48.8 meter wind |
|---|---|---|
| 1 | Wirth Park wiresonde | Interpolated between test area 2 meter wind and wind measured at 77.4 meters downtown. |
| 2 | Wirth Park wiresonde | Same as test no. 1. |
| 3 | St. Cloud 2100 Radiosonde. | Same as test no. 1. |
| 4 | Same as test no. 3 | Same as test no. 1. |
| 5 | Wirth Park wiresonde | Measured on the roof of a downtown 48.8 meter building. |
| 6 | Business wiresonde | Interpolated between test area 2 meter wind and a wind measured on the top of a downtown 122 meter building. |
| 7 | Business wiresonde | Same as test no. 6. |
| 8 | Residential wiresonde | Interpolated between test area 2 meter wind and St.Cloud 305 meter pilot balloon sounding wind (2100 CST). |
| 9 | Residential wiresonde | Same as test no. 8. |
| 10 | St.Cloud 2100 CST radiosonde | Same as test no. 8. |
| 11 | Same as test no. 10 | Same as test no. 8. |
| 12 | Residential wiresonde | Measured on a 48.8 meter building just north of Clinton School. |
| 13 | Residential wiresonde | Same as test no. 12. |
| 14 | Business wiresonde | Same as test no. 8. |
| 15 | Business wiresonde | Same as test no. 8. |

TABLE XIV

1953 MINNEAPOLIS TEST RESULTS
(Where Q is fluorescent particle source strength, $\bar{U}$ is mean wind speed, T is temperature, $\theta$ is potential temperature, Ri is Richardson's number, and $i_z$ is the vertical intensity of turbulence.)

values of "b" (tests 14 and 9 respectively) were calculated from average dosages which were all greater than eight.

There seems to be no correlation between high wind speed and large values of intensity of turbulence. However, there does appear to be a relationship between Richardson's number and the intensity of turbulence as seen in Table XVI. To arrive at the Minneapolis results seen in Table XVI, eleven nighttime city line source tests were used. A linear relationship was assumed between Richardson's number and the value of $i_z$ obtained by solving equation (7). Note that the value for $\bar{U}$ used in this equation is the average of the two meter and 48.8 meter winds. Most of the aerosol clouds were at least 53 meters thick. Vertical sampling ended at that level.

# TABLE XV

## MINNEAPOLIS (MSP) AVERAGE LINE SOURCE DOSAGES (IN PARTICLES MINUTES PER LITER) AND COEFFICIENT (COEF.) OF VARIABILITY

| MSP Test no. | Dist. in meters | | | | | | | | | | | Avg. Coef. or dosage | Avg. no. Samplers |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1799 | 3049 | 4634 | 6403 | 7927 | 9879 | | | | | | |
| 1 | Coef. of variability | .188 | .320 | .420 | .520 | .070 | .232 | | | | | .288 | |
| | Mean dosage | 26 | 19 | 13 | 12 | 7 | 7 | | | | | 13.8 | 3.5 |
| 2 | Coef. of variability | .338 | .425 | 1.222 | .526 | | | | | | | .628 | |
| | Mean dosage | 41 | 27 | 18 | 10 | 1 | 0 | | | | | 19.4 | 4 |
| | Dist. in meters | 457 | 1829 | 3354 | 4878 | 7013 | 10062 | 11891 | | | | | |
| 3 | Coef. of variability | .614 | .273 | .438 | .211 | .528 | .623 | .299 | | | | .428 | |
| | Mean dosage | 81 | 30 | 22 | 14 | 7 | 8 | 7 | | | | 24.1 | 6 |
| 4 | Coef. of variability | .511 | .319 | .255 | .336 | .720 | .283 | | | | | .404 | |
| | Mean dosage | 63 | 21 | 7 | 8 | 3 | 5 | | | | | 17.8 | 5 |
| | Dist. in meters | 457 | 915 | 1677 | 2439 | 4055 | 5793 | 7622 | 9150 | 10671 | 12501 | | |
| 5 | Coef. of Variability | .266 | .428 | .425 | .439 | .205 | .591 | .229 | .260 | .426 | .439 | .371 | |
| | Mean dosage | 609 | 386 | 150 | 123 | 79 | 69 | 52 | 55 | 49 | 40 | 161 | 5 |
| | Dist. in meters | 183 | 311 | 451 | 552 | 735 | 1009 | 1140 | 1287 | 1530 | | | |
| 6 | Coef. of variability | .476 | .212 | .424 | .296 | .337 | .396 | .382 | .182 | .289 | | .333 | |
| | Mean dosage | 271 | 174 | 152 | 136 | 96 | 69 | 56 | 56 | 50 | | 118 | 6.7 |
| | Dist. in meters | 183 | 305 | 457 | 549 | 701 | 869 | 1174 | 1326 | | | | |
| 7 | Coef. of variability | .474 | .297 | .282 | .244 | .380 | .183 | .346 | .363 | | | .321 | |
| | Mean dosage | 214 | 133 | 109 | 78 | 46 | 48 | 38 | 28 | | | 87 | 6 |
| | Dist. in meters | 137 | 244 | 351 | 457 | 762 | 1161 | | | | | | |
| 8 | Coef. of variability | .516 | .177 | .258 | .285 | .420 | .303 | | | | | .326 | |
| | Mean dosage | 240 | 130 | 84 | 75 | 52 | 34 | | | | | 102 | 5 |
| 9 | Coef. of variability | .403 | | .308 | .042 | .224 | .099 | | | | | .215 | |
| | Mean dosage | 216 | | 111 | 72 | 63 | 41 | | | | | 100 | 4.6 |
| | Dist. in meters | 137 | 244 | 351 | 457 | 555 | 762 | 835 | 908 | 1006 | 1311 | 2317 | |
| 10 | Coef. of variability | .436 | .368 | .423 | .241 | .121 | .178 | .224 | .315 | .523 | .129 | .268 .293 | |
| | Mean dosage | 213 | 105 | 62 | 44 | 43 | 41 | 32 | 26 | 26 | 16 | 9 56 | 5.6 |
| 11 | Coef. of variability | .585 | .275 | .352 | .408 | .353 | .086 | .274 | .117 | .288 | .543 | 1.810 .463 | |
| | Mean dosage | 304 | 96 | 87 | 73 | 53 | 52 | 44 | 40 | 32 | 24 | 4 73.5 | 5.6 |
| | Dist. in meters | 91 | 183 | 488 | 793 | 1097 | 1524 | 1677 | 1875 | 2149 | 2805 | | |
| 12 | Coef. of variability | .629 | .358 | .266 | .207 | .249 | .530 | .657 | | | | .414 | 9 |
| | Mean dosage | 1214 | 336 | 144 | 97 | 79 | 59 | 43 | 38 | 38 | 39 | 282 | |
| 13 | Coef. of variability | .889 | .402 | .297 | .145 | .258 | .321 | .247 | | | | .365 | 9.6 |
| | Mean dosage | 2088 | 458 | 202 | 119 | 118 | 88 | 81 | 80 | 66 | 62 | 450 | |
| | Dist. in meters | 122 | 537 | 784 | 936 | | | | | | | | |
| 14 | Coef. of variability | .498 | .850 | .366 | .642 | | | | | | | .589 | |
| | Mean dosage | 331 | 72 | 31 | 19 | | | | | | | 113.2 | 3.5 |
| 15 | Coef. of variability | 1.207 | .416 | .239 | .155 | | | | | | | .504 | |
| | Mean dosage | 298 | 61 | 40 | 37 | | | | | | | 109 | 3.3 |
| 16 | Dist. in meters | 61 | 259 | 549 | 1067 | 1174 | 1280 | | | | | | |
| 16 | Coef. of variability | .481 | .409 | .153 | .142 | .164 | .181 | | | | | .255 | |
| | Mean dosage | 211 | 110 | 34 | 23 | 18 | 15 | | | | | 68.4 | 4 |

## TABLE XVI

### ESTIMATION OF $i_z$ FROM RICHARDSON'S NUMBER

| | No. of cases | Eqn. no. | Regression line | Standard error deg. (S.E.) | Mean $i_z$ degrees (E.) | (S.E.) (E.) |
|---|---|---|---|---|---|---|
| Minneapolis | 11 | (9) | $i_z = 24.91(.43 - Ri.)$ | 1.99 | 9.82 | .20 |
| Dallas (45.7 met.) | 34 | (10) | $i_z = 7.77(.64 - Ri.)$ | 1.12 | 3.97 | .28 |

Comparison of mean values of Ri. and $i_z$ by city section in Minneapolis:

| City Section: | Citywide | Industrial | Suburb | Downtown | All Cases |
|---|---|---|---|---|---|
| No. of cases | 5 | 2 | 6 | 2 | 15 |
| Richardson's no. | .089 | -.018 | .024 | -.019 | |
| $i_z$ in degrees | 6.8 | 10.6 | 14.4 | 9.82 | |

As a basis for comparison, the bivane-measured $i_z$ at 45.7 meters, collected during the 1961 Dallas tower tests, was compared to the Richardson's number calculated for the layer between 9.0 and 91.5 meters. Data average times were ten minute periods. Equation (9) for Minneapolis, and equation (10) for Dallas, can be seen in Table XVI. The difference between the two equations can be explained by the difference in roughness over the city of Minneapolis and the rolling Dallas plain. This is true because the intensity of turbulence is a function of Richardson's number, roughness and height above the ground [9].

In the Minneapolis tests, predominantly zero dosages occur only at 9879 meters in test two, and 2317 meters for test eleven.

2. St. Louis

Three successful two meter level line source tests were conducted in St. Louis. Here, for Richardson's number calculations, the two to 18.3 meter layer is used. To obtain an estimate of a 48.8 meter wind speed, the two lower level winds (two and 18.3 meter) are used to make a linear extrapolation on log-log paper. The mean wind speed used in equation (7) to estimate $i_z$ is the average of the observed two meter wind speed and the estimated 48.8 meter wind speed. Observation points for the 18.3 meter wind speeds were as follows:

a. For the two suburban tests, conducted 4100 meters west of the downtown area, the measurements were made at a building top in the suburb.

b. For the downtown tests, the wind speed measurements were taken from a building top, 3300 meters northwest of the downtown section. All wiresonde temperature profiles used were taken at the northern edge of the downtown area from the top of a two story building on the corner of eighth and Delmar. This is very near the center of the St. Louis heat island.

Results of the St. Louis tests appear in Tables XVII and XVIII. The estimated values of $i_z$ of 10.9, 10.0, and 8.1 degrees compare to values calculated from formula (9) of 12.8, 13.3, and 10.8 degrees, respectively. Hence the values estimated using formula (9) average 1.3 times too high.

It is interesting to note that the average 2-48.8 meter wind speed for the St. Louis downtown test, is 85 per cent of the average Minneapolis downtown speed, but the value of $i_z$ in St. Louis is 56 per cent of the average downtown Minneapolis value. Hence equation (9) appears to be a more adequate basis of estimating the St. Louis values of $i_z$ than the simple wind speed.

There were no surface sampling lines with predominantly zero dosages in St. Louis for distances up to three thousand meters from source.

## TABLE XVII

## ST. LOUIS (STL) TEST RESULTS

| STL Test no. | Effective Q in $10^{10}$ part./m. | Area | Date | Time CST | Maximum sampling distance in meters | 2 meter $\bar{U}$ m/sec | 2 meter T °C | 2-18.3 meter $\partial\theta/\partial z$ °C/m. | 2-18.3 meter $\partial U/\partial z$ $sec^{-1}$ | Ri. | 2-48.8 m. $\bar{U}$ m/sec | b | $i_z$ deg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .1408 | Suburb | 29 May | 2335 | 3049 | 0.89 | 26.7 | -.0237 | .0978 | -.081 | 2.30 | .80 | 10.9 |
| 2 | .0446 | " | 30 May | 0335 | 3049 | 0.89 | 24.4 | -.0169 | .0733 | -.104 | 2.01 | .78 | 10.0 |
| 3 | .1741 | Down town | 15 Jun | 2227 | 2320 | 1.52 | 27.2 | -.0009 | .1792 | -.001 | 3.20 | 1.57 | 8.1 |

# TABLE XVIII

## ST. LOUIS (STL) AND WINNIPEG (WP) AVERAGE LINE SOURCE DOSAGES (IN PARTICLES MINUTES/LITER) AND COEFFICIENTS (COEF.) OF VARIABILITY

| STL Test no. | Dist. in meters | 91 | 427 | 808 | 1055 | 1207 | 1674 | 3049 | | | | Avg. Coef. or dosage | Avg. no. samplers |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Coef. of variability | .728 | .233 | .115 | .237 | .232 | .098 | .102 | | | | .249 | |
| | Mean dosage | 524 | 148 | 90 | 80 | 66 | 59 | 33 | | | | 167 | 5.4 |
| 2 | Coef. of variability | .715 | .154 | .174 | .093 | .242 | .200 | .052 | | | | .233 | |
| | Mean dosage | 247 | 63 | 38 | 28 | 27 | 26 | 14 | | | | 63 | 5.3 |
| | Dist. in meters | 1106 | 1358 | 1453 | 1700 | 1855 | 2099 | 2320 | | | | | |
| 3 | Coef. of variability | .264 | .340 | .261 | .154 | .164 | .204 | .334 | | | | .246 | |
| | Mean dosage | 130 | 114 | 84 | 66 | 57 | 55 | 42 | | | | 78 | 6.86 |
| WG Test no. | Dist. in meters | 915 | 2134 | 3658 | 6097 | 7622 | | | | | | | |
| 1 | Coef. of variability | .750 | .593 | .461 | .113 | | | | | | | .479 | |
| | Mean dosage | 412 | 230 | 242 | 92 | | | | | | | 244 | 4.0 |
| 2 | Coef. of variability | .740 | .333 | .561 | .092 | .269 | | | | | | .399 | |
| | Mean dosage | 338 | 142 | 85 | 35 | 22 | | | | | | 124 | 4.8 |
| | Dist. in meters | 1219 | 3049 | 4573 | 6097 | 7317 | | | | | | | |
| 3 | Coef. of variability | 1.127 | .557 | .167 | .109 | .833 | | | | | | .559 | |
| | Mean dosage | 37 | 7 | 6 | 9 | 3 | | | | | | 12.3 | 4.4 |
| 4 | Coef. of variability | .760 | .809 | .431 | .203 | .288 | | | | | | .498 | |
| | Mean dosage | 32 | 22 | 11 | 6 | 6 | | | | | | 15.3 | 4.8 |
| | Dist. in meters | 122 | 305 | 549 | 854 | 1280 | 1829 | | | | | | |
| 5 | Coef. of variability | 1.011 | .366 | .070 | .113 | .144 | | | | | | .341 | |
| | Mean dosage | 1301 | 325 | 213 | 161 | 113 | 103 | | | | | 369 | 4.8 |
| 6 | Coef. of variability | .382 | .112 | .426 | .285 | .241 | | | | | | .289 | |
| | Mean dosage | 507 | 189 | 90 | 68 | 54 | 46 | | | | | 159 | 6.3 |
| 7 | Coef. of variability | .109 | .274 | .177 | .545 | .694 | | | | | | .360 | |
| | Mean dosage | 225 | 104 | 36 | 30 | 18 | 12 | | | | | 71 | 5.7 |
| 8 | Coef. of variability | .378 | .507 | .563 | .495 | .265 | | | | | | .442 | |
| | Mean dosage | 353 | 119 | 51 | 53 | 21 | 3 | | | | | 100 | 5.5 |
| | Dist. in meters | 92 | 274 | 427 | 610 | 762 | 915 | 1097 | 1280 | 1463 | 1646 | | |
| 9 | Coef. of variability | .366 | .258 | .959 | .463 | .190 | .135 | .246 | .245 | .342 | .220 | .345 | |
| | Mean dosage | 5542 | 2305 | 2679 | 943 | 1466 | 1567 | 1162 | 1095 | 987 | 962 | 871 | 8.5 |
| | Dist. in meters | 183 | 335 | 518 | 671 | 838 | 1006 | 1174 | 1341 | 1524 | | | |
| 10 | Coef. of variability | .458 | .426 | .500 | .421 | .467 | .575 | .823 | .471 | .948 | | .565 | |
| | Mean dosage | 1003 | 233 | 173 | 87 | 50 | 24 | 26 | 16 | 20 | | 181 | 9.7 |

3. Winnipeg

There were ten successful line source tests in Winnipeg. Results appear in Tables XVIII and XIX. In Winnipeg, the lack of measured 30.5 meter winds resulted in relatively poor estimates of Richardson's number.

To obtain an estimated 30.5 meter wind, an interpolated value was obtained by plotting both the Winnipeg 2 meter wind speed and the Winnipeg pilot balloon three-hundred and five meter wind speed on log-log paper and making a linear interpolation. For the citywide and country-side tests, wiresonde temperatures were measured from the roof of the Dominion Motors Building, on the edge of the downtown, tall building, area. If 0.250 is assumed to be the largest possible positive Richardson's number, and this value is substituted for the values of 1.717 and 0.509 in tests one and two, then the correlation between the in-city estimated values of $i_z$ in Winnipeg and corresponding values calculated from equation (9) is 0.89. The observed in-city mean value of $i_z$ is 10.64 compared to a calculated mean value of 9.71 degrees.

TABLE XIX

1953 WINNIPEG TEST RESULTS

| Winnipeg Test No. | Effective Q in $10^{10}$ part./meter | Area | Date | Time CST | Maximum Sampling distance meters | 2 meter $\bar{U}$ m/sec | 2 meter T °C | 2-30.5 meter $\partial\theta/\partial z$ °C/m | 2-30.5 meter $\partial U/\partial z$ $Sec^{-1}$ | Ri. | 2-48.8m $\bar{U}$ M/sec | b | $i_z$ deg. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .2588 | City- | 23 Jul | 2035 | 6,098 | 1.38 | 16.1 | .1348 | .0515 | 1.717 | 2.37 | .80 | 6.0 |
| 2 | .2081 | wide | 23 Jul | 2307 | 7,622 | 1.56 | 15.6 | .0351 | .0484 | .509 | 2.57 | 1.23 | 6.6 |
| 3 | .1773 | " | 1 Aug | 1235 | 7,622 | 2.73 | 20.0 | -.0046 | .0967 | -.016 | 5.12 | 1.35 | 13.9 |
| 4 | .1678 | " | 1 Aug | 1450 | 7,622 | 1.92 | 20.0 | -.0074 | .0827 | -.036 | 4.16 | 1.12 | 12.0 |
| 5 | .3037 | Down- | 21 Jul | 2105 | 1,829 | 1.48 | 19.4 | .0042 | .1049 | .013 | 3.60 | .96 | 9.2 |
| 6 | .1598 | town | 21 Jul | 2305 | 1,829 | 1.83 | 17.2 | -.0062 | .1155 | -.016 | 4.00 | .92 | 9.3 |
| 7 | .2695 | " | 25 Jul | 1305 | 1,829 | 3.08 | 22.2 | Msg. | Msg. | Msg. | 4.33 | 1.09 | 19.2 |
| 8 | .3182 | " | 25 Jul | 1550 | 1,829 | 2.59 | 22.2 | -.0636 | .1186 | -.150 | 4.51 | 1.56 | 17.5 |
| 9 | .3566 | Country- | 3 Aug | 2145 | 1,646 | 2.24 | 13.9 | .0925 | .0952 | .350 | 4.36 | .58 | 5.2 |
| 10 | .2329 | side | 2 Aug | 1620 | 1,646 | 2.24 | 23.9 | -.0151 | .0484 | -.216 | 3.13 | 1.87 | 7.7 |

It is interesting to note the relative surface dosages occurring for the stable test Winnipeg countryside (test 9). The two to 30.5 meter increase of temperature with height is 0.06°C per meter. The associated Richardson's number is 0.350. The normalized dosage ($D\bar{U}x/Q$) at approximately one mile is 116.16, or nine times the smallest nighttime in-city value of 12.64 (Winnipeg test 6), and thirty-one times the smallest Minneapolis value. The Winnipeg test 9 value of $i_z$ is a small 5.2° and the value of b is only 0.58 so that the rate of dosage decrease with distance is relatively small.

For the Winnipeg nighttime line source tests, there are no predominantly zero dosages for distances up to 7600 meters.

## E. DOSAGE CHANGE RATE WITH DISTANCE OVER CITIES

It is of some interest to relate values of "b" estimated from the formula; (average cross-wind dosage) = $kx^{-b}$, to values of the intensity of turbulence and two to 48.8 meter average wind speed. This is done in Table XX. The in-city nighttime value of "b" is appreciably greater than one only in the downtown St. Louis test (where b = 1.57) and in one Minneapolis industrial area test (where b = 1.34). The day-

### TABLE XX

### COMPARISON OF b IN THE FORMULA $\sigma_z = kx^{-b}$ to $i_z$ AND $\bar{U}$

| City | Area | No. of cases | | b | | $i_z$ degrees | | 2-48.8 meter $\bar{U}$ in m/sec | | Ri | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Day | Night | Day | Night | Day | Night | Day | Night | Day | Night |
| Minneapolis | Citywide | | 5 | | .92 | | 6.9 | | 5.57 | | .089 |
| | Downtown | | 2 | | .86 | | 14.9 | | 3.75 | | -.019 |
| | Suburb | | 6 | | .99 | | 12.2 | | 3.75 | | .024 |
| | Industrial | | 3 | | 1.13 | | 13.2 | | 4.00 | | -.018 |
| St. Louis | Downtown | | 1 | | 1.57 | | 8.1 | | 3.20 | | -.001 |
| | Suburb | | 2 | | .79 | | 10.4 | | 2.16 | | -.092 |
| Winnipeg | Citywide | 2 | 2 | 1.23 | 1.01 | 13.0 | 6.3 | 4.64 | 2.47 | -.054 | .626 |
| | Downtown | 2 | 2 | 1.32 | .94 | 18.3 | 9.2 | 4.42 | 3.80 | -.072 | -.015 |
| | Countryside | 1 | 1 | 1.90 | .58 | 7.7 | 5.2 | 3.13 | 4.36 | -.058 | .252 |

time values of "b" in Winnipeg are all appreciably greater than one. The lowest value of "b" is seen to be the nighttime value of 0.58 in the Winnipeg countryside. The next lowest value is found over the St. Louis suburb (0.79) and is associated with a Richardson's number of -0.092. There does not appear to be a clear relationship of "b" to the intensity of turbulence.

## F. CONTINUOUS POINT SOURCE RESULTS AND COMPARISON TO LINE SOURCE FINDINGS

To analyze five minute continous point source data, cross-wind integrated dosages were used. These values are somewhat less reliable than the average cross-wind dosages resulting from instantaneous line sources. Hence the estimates of $i_z$ and "b" are less dependable. The equations (11) and (12) used to estimate $i_z$ are:

$$\text{Cross-wind integrated dosage (CWID)} = \sqrt{(2/\pi)}\,Q/(\sigma_z \bar{U}), \text{ and} \qquad (11)$$

$$\sigma_z = i_z x, \qquad (12)$$

where: $\sigma_z$ is the vertical standard deviation of the aerosol cloud, $i_z$ is the vertical intensity of turbulence, $\bar{U}$ is the mean two meter wind speed and Q is the source strength, x is the distance downwind from source.

"b" is estimated from; (13) (CWID) = constant $(x^{-b})$.

Results are seen in Tables XXI and XXII. The average value of b = 1.16 for all nighttime cases compares to the instantaneous line source value of 0.98. A city-by-city comparison of point and line source "b" values appears in Table XXII. The nighttime values of "b" for point sources are consistently larger than similar values for instantaneous line sources. Also, the point source values of $i_z$ are generally smaller than values estimated from line sources on the same nights.

## G. VERTICAL DOSAGE DISTRIBUTIONS

Vertical dosage distributions were not measured for all of the 1953 city tests. Results of one Minneapolis point source and four line source tests are summarized in Table XXIII. At 549 meters from source, the vertical distribution for a suburban five minute continuous point source is far from normal. At 915 meters from source, dosages from two nighttime downtown line sources were used. Here,

TABLE XXI

FIVE MINUTE CONTINUOUS POINT SOURCE CALCULATIONS BASED ON OBSERVED CROSS-WIND-INTEGRATED DOSAGES

| Area | Date | Time | Maximum sampling distance meters | Turbulence intensity $i_z$ deg. Day | Turbulence intensity $i_z$ deg. Night | Mean two meter wind speed m/sec Day | Mean two meter wind speed m/sec Night | "b" Day | "b" Night |
|---|---|---|---|---|---|---|---|---|---|
| Minneapolis | 1953 | | | | | | | | |
| Citywide | 31 Aug | 2115 | 12,806 | | 7.1 | | .96 | | .94 |
| Downtown | 28 Aug | 2235 | 1,829 | | 12.3 | | 1.34 | | 1.43 |
| Suburb | 3 Mar | 2022 | 1,220 | | 4.4 | | 1.25 | | 1.65 |
| | 18 Mar | 2125 | 1,067 | | 14.8 | | 3.35 | | 1.08 |
| | 25 Aug | 2248 | 1,829 | | 5.2 | | 2.28 | | .77 |
| | | | Avg. | | 8.76 | | 1.84 | | 1.17 |
| St. Louis | 1953 | | | | | | | | |
| Downtown | 15 Jun | 2045 | 1,524 | | 6.6 | | 2.79 | | 1.5 |
| Suburb | 30 May | 0126 | 1,524 | | 5.5 | | 1.79 | | .9 |
| | | | Avg. | | 6.05 | | 2.29 | | 1.2 |
| Winnipeg | 1953 | | | | | | | | |
| Downtown | 21 Jul | 2210 | 2,439 | | 11.4 | | 1.94 | | 1.06 |
| | 21 Jul | 1446 | 1,220 | 9.5 | | 3.75 | | 1.11 | |
| Country- | 3 Aug | 2057 | 1,829 | | 2.2 | | 4.47 | | 1.18 |
| side | 3 Aug | 1435 | 1,829 | 3.9 | | 3.75 | | 1.89 | |
| | 3 Aug | 1720 | 1,829 | 2.5 | | 2.90 | | 1.8 | |
| | | | Avg. | 5.3 | 6.8 | 3.49 | 3.20 | 1.6 | 1.12 |
| | Avg. all cities | | | 5.3 | 7.7 | 3.49 | 2.24 | 1.6 | 1.16 |

the distribution of dosages is essentially normal in spite of the associated unstable (super-adiabatic) lapse rate and an average value of estimated $i_z$ equal to 14.4 degrees. A rough estimate of the aerosol cloud vertical standard deviation ($\sigma_z$) here is (129.6/2.15) or 60.4 meters. The calculated value of $\sigma_z = 3 i_z x$ is 291 meters. For the vertical dosage profile at 3354 meters, two instantaneous line source tests were used. Measured dosages are almost uniformly distributed with height. The average ground dosages for these tests varied almost

TABLE XXII

COMPARISON OF TURBULENCE INTENSITY AND b FOR LINE AND POINT SOURCES

| Nighttime tests Minneapolis | | | | | | Nighttime tests St. Louis | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Line Source | | | Point Source | | | Line Source | | | Point Source | | |
| No. of cases | $i_z$ | b | No. of cases | $i_z$ | b | No. of cases | $i_z$ | b | No. of cases | $i_z$ | b |
| 16 | 11.5 | .98 | 3 | 6.8 | 1.15 | 3 | 10.9 | 1.05 | 2 | 6.1 | 1.2 |

| Daytime tests Winnipeg | | | | | | Nighttime tests | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Line Source | | | Point Source | | | Line Source | | | Point Source | | |
| No. of cases | $i_z$ | b | No. of cases | $i_z$ | b | No. of cases | $i_z$ | b | No. of cases | $i_z$ | b |
| 3 | 17.04 | 1.5 | 3 | 5.3 | 1.6 | 5 | 9.6 | .9 | 2 | 6.6 | 1.12 |

TABLE XXIII

VERTICAL DOSAGE DISTRIBUTION IN MINNEAPOLIS

| Location or Test Number | | | | | | |
|---|---|---|---|---|---|---|
| Suburb | Distance from source | 549 meters | | | | |
| | Height of sampler, meters | 1.5 | | 3 | 6.1 | 10.6 |
| | Average dosage, part.min. per liter | 5.44 | | 4.41 | 3.78 | 3.53 |
| | Per cent of 1.5 meter dosage | | | 81 | 69 | 65 |
| 6 and 7 | Distance from source | 915 meters | | | | |
| | Height of sampler, meters | 38 | 53.3 | 83.3 | 114 | 129.6 |
| | Per cent of 1.5 meter dos. | 71 | 63 | 50 | 30.5 | 10 |
| 4 and 5 | Distance from source | 3354 meters | | | | |
| | Height of sampler, meters | 38 | 53.3 | 68.6 | 83.8 | 129.6 |
| | Per cent of 1.5 meter dos. | 96.5 | 115 | 130 | 113 | 107 |

linearly with distance, having an average "b" value of 0.86 for the 915 meter distance and 0.88 for the 3354 meter distance.

In St. Louis, there was vertical sampling, 1768 meters from source in test 3, however there was very little variation of dosages with height up to 53 meters above street level.

In Winnipeg, for the nighttime in-city tests, there was almost no variation of dosages with height for distances from 396 to 3841 meters from source and from the height of 11 to 42 meters above the ground. The tests considered here are the Winnipeg line source tests 1, 2, 5, and 6.

## H. RANDOMNESS OF SURFACE DOSAGES

The crosswind surface sampling lines used in the city line source tests make it a simple matter to check the randomness of measured dosages. Twenty seven, in-city tests were used to make estimates of dosage random variability. (Refer to Tables XV and XVIII for individual test results.) There were an average of six to seven crosswind sampling lines per test, each line containing an average of five to six samplers. The coefficient of variability, used as a measure of the randomness of dosages, is defined as the standard deviation of the dosages for each crosswind line divided by the mean dosage for that line. The average coefficients of variability, shown in Table XXIV, present a clearer picture of the differences between cities and between sections within a given city.

TABLE XXIV

IN-CITY DOSAGE COEFFICIENTS OF VARIABILITY (RATIO OF STANDARD DEVIATION OF DOSAGES TO THE MEAN FOR CONSTANT DISTANCE FROM SOURCE)

| Minneapolis | | St. Louis | | Winnipeg (all cases) | |
|---|---|---|---|---|---|
| Citywide | .407 | | | | |
| Suburb | .346 | Suburb | .241 | Day | .485 |
| Downtown | .319 | Downtown | .246 | Night | .377 |
| Industrial | .514 | | | | |
| Avg. | .381 | | .243 | | .431 |

## I. COMPARISON OF THE 1953 CITY TEST RESULTS WITH THE 1964-1966 FORT WAYNE DIFFUSION TEST RESULTS

A series of elevated line source tests were conducted over Ft. Wayne, Indiana during 1964-1966 [10]. Vectorvane measurements of turbulence data were made at two towers, the Wane TV tower northwest (and upwind for these tests) of Fort Wayne and a tower located on top of the General Telephone building in the downtown section. Two meter dosages were measured with rotorods. Dosage calculations prepared using equation (1) and the method outlined in Section II, correspond reasonably well to observed dosages if the Wane tower data is used, less well if the downtown tower data is used.

Calculations of dosages prepared from upwind tower data were within a factor of two of in-city dosages 56 per cent of the time and within a factor of three 85 per cent of the time. The skill score for the prediction of the presence or absence of dosages equal to, or greater than eight particles minutes per liter, is 0.58 (compared to 0.63 for the 1961 Dallas Tower elevated line source tests) and the per cent correct is 88 (compared to 84 for Dallas). Hence, the Hay-Smith method of calculating the cloud standard deviation works reasonably well here, without making any special corrections for the presence of the city.

The Travelers Research Center, Inc. research personnel, who prepared the report on the Ft. Wayne tests [10], distinguished between aerosol clouds which maintained a bell-shaped distribution in the vertical, and those which were uniformly mixed with height. The in-city coefficient of variability of surface dosages for the former is 0.417 and for the latter, the coefficient is 0.304. Corresponding Ft. Wayne country side variabilities are respectively 0.413 and 0.440. These figures are very similar to the coefficients of variability obtained from the 1953 test data. St. Louis was the largest city, hence the city over which uniform distribution of dosages with height is most probable. The St. Louis coefficient of variability of 0.243 (Table XXIV) is also the smallest, as might be expected.

Since the vertical intensity of turbulence ($i_z$) was not measured for the 1953 city tests, it was necessary to use observed dosages and winds in equation (1) to solve for $i_z$. This was done for the calculations in Tables XIV, XVII and XIX on the assumption that the Hay-Smith method of calculating standard deviation [2] is valid for application to the 1953 tests. To calculate Richardson's number, Minneapolis wiresonde temperature data was used and wind speeds were measured from car-top anemometer installations for the two meter level and roof-top installations on tall buildings for the upper level. The intensity of turbulence and Richardson's number were assumed to be linearly related. Equation (9), in Table XVI, is the result of least squares fit to the data. For the Fort Wayne dosage calculations, the upwind TV tower bivane data produced reasonably accurate dosage calculations for surface dosages. Hence it is of some interest to see how $i_z$ and Richardson's number data observed on the tower were related. For this purpose, the TV tower 30.5 meter and 91.5 meter. Fort Wayne temperatures and wind speeds were used to calculate Richardson's number and to relate that number to the vectorvane measurement of $i_z$ at 61 meters. Half hour average wind speeds and temperatures were used. The number of tests involved was twenty The resulting least squares formula for $i_z$ is: (Refer to note after equation (4))

$$i_z = 17.567(.284 - Ri.) \tag{13}$$

where: (standard error/mean) $i_z$ = .31. (Equation (13) is similar to the Minneapolis formula seen in Table XVI; namely:)

$$i_z = 24.91(.43 - Ri.) \tag{9}$$

Ft. Wayne countryside two meter dosages are not significantly different from city values, if the aerosol cloud remains bell-shaped in the vertical profile. However, if the cloud is uniformly mixed with height over the city, countryside dosages are significantly different by the Willcoxon rank test [5] at the four per cent level. Also, in this case, the countryside dosages average twenty per cent higher than the city dosages. The large country-to-city difference found at Winnipeg is not found at Ft. Wayne. This could be explained by a strong countryside low level temperature inversion which trapped the surface line source aerosol cloud close to the ground at Winnipeg. A similar low level inversion over the countryside at Fort Wayne could have limited the amount of the aerosol reaching the ground.

## J. SUMMARY AND CONCLUSIONS

In summary, nighttime instantaneous line source estimates of $i_z$ in Minneapolis, St. Louis, and Winnipeg diffusion tests vary from 5.7 to 18.5 degrees. The estimated variations of the aerosol cloud vertical standard deviation ($\sigma_z$), with distance, is very close to linear with an indication of an appreciably larger rate only in downtown St. Louis. There appears, from this limited sample, to be a simple relationship of Richardson's number to the vertical intensity of turbulence ($i_z$) for values of positive Richardson's number of 0.250 or less. The relationship comes from the Minneapolis data and checks out with reasonable success on St. Louis and Winnipeg data. A similar formula obtained from Ft. Wayne 1964-1966 data (equation 13) corresponds closely to the Minneapolis formula (equation 9).

The close correspondence of calculated and observed dosages for the Ft. Wayne test justifies the use of the Hay-Smith method of calculating the cloud standard deviation. It appears, then, that one equation for the relationship of Richardson's number to $i_z$ is applicable to all the cities considered here, and that an accurate enough value of Richardson's number for the lowest fifty meters can be obtained by the used of wiresonde temperature measurements and winds measured on the tops of cars and on the tops of buildings.

## SECTION V. A USE OF EDDY DIFFUSIVITY TO MAKE DOSAGE CALCULATIONS

### A. BACKGROUND

The eddy diffusivity (K) can also be used to make dosage calculations. There has been very little written on the method of determining the value of eddy diffusivity between the top of the surface boundary layer (about sixteen meters) and the gradient wind level. Wu developed and tested such a method [11] . She derived a formula for eddy diffusivity for heat ($K_H$) from the equations of motion. Values of $K_H$, calculated from the Wu equation (equation (18) ), were then used in a numerical integration, finite difference model, to prepare twenty four hour temperature forecasts for an atmospheric surface layer 427 meters thick. The marked accuracy of these forecasts suggests the merit of using values of $K_H$ calculated in this manner to prepare diffusion dosage computations. Such calculations are made in this section and are then compared to those made using the Hay-Smith method of calculating the cloud standard deviation [2] in the Calder dosage equation for an elevated line source. (Refer to Section II, equation (1) ). Since the use of a constant value for $K_H$ is valid only for large diffusion times, all comparisons are made for such times.

### B. DERIVATION OF THE EDDY DIFFUSIVITY FORMULA

Starting with the energy equation (refer to equation 2.28 in Lumley and Panofsky [12] ), it can be assumed that (1) the rate of change of mechanical turbulent energy with time is zero and (2) there is horizontal homogeneity, steady mean motion, and no change of wind direction with height. With these approximations, the equation (14) is used for mechanical energy.

$$0 = \overline{-u'w'}\frac{\partial \overline{U}}{\partial z} + \frac{g}{T_o}\overline{w'\theta'} - \nu\frac{\partial u_i \partial u_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial z}\left((e + p/\rho_o)\, w'\right) \qquad (14)$$

| Term No. | 1. | 2. | 3. | 4. | 5. |
|---|---|---|---|---|---|

(Refer to equation 2.38 [12] )

where: $w' = w - \overline{w}$ = vertical wind speed fluctuation
$u' = U - \overline{U}$ = longitudinal horizontal wind speed fluctuation
$U$ = instantaneous horizontal wind speed

$\overline{U}$ = mean horizontal wind speed
$\theta' = \theta - \overline{\theta}$ = potential temperature fluctuation
$u_i$ = wind speed fluctuation in the i direction
$x_j$ = distance in the j direction

i and j are indices with values of 1, 2 or 3 where 1 stands for longitudinal direction, parallel to the mean wind direction, 2 stands for lateral direction, perpendicular to the mean wind direction and 3 stands for vertical direction (positive upwards)
e = mechanical energy = $1/2\ \overline{(u'^2)}$
$\nu$ = dynamic viscosity of air
p = pressure fluctuation
$T_o$ = mean absolute temperature for the layer considered
$\rho_o$ = mean air density for the atmospheric layer considered

Term 1. in equation (14) can be rewritten as equation (15).

$$\overline{u'w'}\ \frac{\partial \overline{U}}{\partial z} = -K_M (\partial \overline{U}/\partial z)^2 \tag{15}$$

Term 2. can be rewritten as equation (16)

$$\frac{g}{T_o}\ \overline{w'\theta'} = -K_H\ (\partial \theta/\partial z)\frac{g}{T_o} \tag{16}$$

where: $K_H$ and $K_M$ are eddy diffusivities for heat and momentum respectively. Term 3. is the term for dissipation of turbulent energy ($\epsilon$). Lumley [12] points out that terms 2. and 4. might be the important ones in the case of free convection; terms 2. and 3. for cases with negligible vertical wind shear; and finally terms 2., 3., and 4. for the inversion case. If terms 4. and 5. are dropped, the result is the final formula for $K_H$ used by Wu.

In a homogeneous region, as the Dallas tower situation is assumed to have been during the 1961 series of diffusion tests, terms 1., 2. and 3. might be the important ones. This is the case where energy produced locally is also dissipated locally. Dropping terms 4. and 5. in equation (14) and substituting equations (15) and (16), respectively, for terms 1. and 2. and energy dissipation ($\epsilon$) for term 3., the resulting equation (17) is:

$$\varepsilon = K_M((\partial U/\partial z)^2 - \frac{K_H}{K_M}\ \frac{g}{T_o}\ \frac{\partial\theta}{\partial z}) \qquad (17)$$

After Blackadar [13], $K_M = \varepsilon^{1/3} \ell^{4/3}$, where $\ell$ is an appropriate length scale defined as:

$\ell = kz/(1 - kz/\lambda)$, k is von Karman's constant (0.4), z is height and $\lambda$ is a constant to be determined.

Substituting the above in equation (17) the result is:

$$K_M = ( (\partial\bar{U}/\partial z)^2 - \frac{K_H g}{K_M T_o}\ (\partial\theta/\partial z) )^{1/2} (kz/(1 + kz/\lambda)^2) \qquad (18)$$

Having derived equation (18), Wu assumed that $K_H = K_M$ and that $\underline{\lambda}$ was a function of vertical thermal stratification. She classified $\lambda$ in terms of stability to get:

$\lambda$ = 100 meters when $\partial\theta/\partial z < 0^oC/m$
$\lambda$ = 30 meters when $0 < \partial\theta/\partial z < 10^{-4}\ ^oC/m$
$\lambda$ = 12.5 meters when $\partial\theta/\partial z > 10^{-4}\ ^oC/m$

Wu then proceeded to use the values obtained from equation (18) in a finite difference form of equation (19)

$$\partial T/\partial t = \frac{\partial}{\partial z} K_H \frac{\partial T}{\partial z} \qquad (19)$$

to numerically calculate the temperatures for a twenty four hour period for the 427 meter atmospheric surface layer. The results are good. The diurnal range for the forecast day varied from about seven degrees centigrade at 350 meters, to nine degrees centigrade at fifty meters. The maximum forecast error was $2^oC$ at fifty meters. The average forecast error was less than $0.5^oC$.

## C. THE USE OF EDDY DIFFUSIVITY TO MAKE DIFFUSION DOSAGE CALCULATIONS

The excellence of the temperature forecasts made with the use of equation (18) suggest that terms 1., 2., and 3. in equation (14) are the important ones for atmospheric conditions similar to those found during the Dallas tower tests. It appears appropriate therefore to use this form of $K_H$ to prepare dosage calculations.

The diffusion dosage equation used here with equation (18), comes from equation (5-86a) in Hinze [14] as follows:

$$D(x, 0, 0) \simeq \frac{Q}{\sqrt{2\pi K_H U x}} \exp(-\bar{U}h^2/4K_H x) \tag{20}$$

For the first comparison, data from the ten Dallas tower tests, which had cross-line sampling at 30 miles, is used. Dosage calculations prepared using $K_H$ are compared to those using the Hay-Smith and Calder models given in Section II. Results follow:

| | Average dosage in particles minutes per liter | Correlation coefficient between calculated and observed dosages |
|---|---|---|
| $K_H$ calculation | 14.33 | .51 |
| Hay-Smith calculation | 11.72 | .49 |
| Observed dosage, avg. | 16.38 | |

The above results are not conclusive. The $K_H$ calculations seem to be slightly better.

A further check is made using Windsoc I data (refer to Section III). In order to derive an estimate of the intensity of turbulence from wind aloft and temperature sounding data, the Richardson's number formula for $i_z$ (Table XVI, equation (10) ) is used. The Windsoc I meteorological data used includes the average value of wind speeds obtained from fourteen pilot balloon soundings taken over the 125 mile square grid. These values are again averaged in time every half hour during the aerosol cloud travel period. One temperature sounding position is used, averaged for the cloud travel time. Results for seven tests and a distance thirty miles from source follow:

| | Average dosage in particles minutes per liter | Correlation coefficient between calculated and observed dosages |
|---|---|---|
| $K_H$ calculation | 13.77 | .30 |
| Richardson's number | | |
| Hay-Smith calculation | 27.53 | .60 |
| Observed | 31.52 | |

Here, the $K_H$ method is not as good as the method involving a value of $i_z$ which is derived from the value of Richardson's number and the use of the Hay-Smith method of calculation of $\sigma_z$ in the Calder diffusion equation.

In an effort to more clearly distinguish between the two methods, it is possible to measure the skill score [5] obtained using each of the methods in predicting that the aerosol cloud would or would not reach the ground in 30 miles. Results follow for thirty two Dallas tower tests.

$K_H$ forecast of the aerosol cloud to reach the ground.

| | | YES | NO | TOTAL |
|---|---|---|---|---|
| Observed | YES | 27 | 0 | 27 |
| | NO | 5 | 0 | 5 |
| | TOTAL | 32 | 0 | 32 |

In this calculation, a dosage of one or more particles minutes per liter is defined as presence of the aerosol cloud at the two meter level. The skill score for the above is zero. Per cent forecast correctly is 74.

Use of the Hay-Smith, Calder method follows:

Hay-Smith, Calder method forecast of aerosol presence at the two meter level.

| | | Forecast | | |
|---|---|---|---|---|
| | | YES | NO | TOTAL |
| Observed | YES | 25 | 2 | 27 |
| | NO | 1 | 4 | 5 |
| | TOTAL | 26 | 6 | 32 |

Skill score = 0.67, per cent correct = 91

The results above indicate that the K method has some merit for predicting dosages resulting from an elevated line source but that it lacks the sensitivity required to predict the time that an elevated line source aerosol cloud first reaches the ground.

## D. CONCLUSION

It can be concluded that the dosage calculations prepared using the form of eddy diffusivity ($K_H$) tested above in an analytic equation for aerosol dosage prediction produces reasonably good results if the aerosol cloud has reached the ground. However, as a predictor of the time when the cloud will reach the ground, the statistical model, which makes use of the Hay-Smith mathematical formula for estimating aerosol cloud standard deviation, appears to be the better of the two. It might be assumed that better calculations would result from using the K method if numerical integration of the dosage equation were used.

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13. ABSTRACT

This report consists of five sections. Section I is an introduction. Sections II through V treat related subjects. Section II demonstrates the accuracy to be expected from diffusion dosage calculations which make use of direct measurements of intensity of turbulence and wind speed. Section III uses a derived expression for the relationship of Richardson's number to intensity of turbulence, and the resulting dosage calculations are discussed. Section IV tests the universality of the derived relationship of Richardson's number to intensity of turbulence. Section V relates the variance of vertical wind speeds at different sites and altitudes to Richardson's number. Section V further treats some of the problems involved in calculating and using eddy diffusivity to make dosage calculations and suggests a way of calculating eddy diffusivity at heights between the top of the surface boundary layer and the gradient wind level.

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